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A Versatile Infra-Red Spectrograph

ROBERT A. OETJEN
Beacon Research Laboratory of The Texas Company, Beacon, New York

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An infra-red spectrograph having sufficient flexibility to permit a wide variety of investigations is described. Its main characteristics follow. Any one of two prisms and two gratings, mounted on a table rotated by a large worm wheel, may readily be put into the path of the collimated radiation. A foreprism spectrometer is built into the instrument in such a way that it may be by-passed. The spectrograph case and the source housing are evacuable. Moving parts in the evacuated chamber are controlled through induction and Autosyn types of motors. This permits control, entirely electrical, from a semi-portable unit outside the spectrograph. The widths of the slits are automatically varied so that the output of the radiation detector thermocouple is approximately the same for all spectral regions if no absorbing material is in the path. The radiation detector is a rapid-response evaporated thermocouple whose output is amplified by a vacuum tube amplifier. A pulsating thermocouple output voltage is obtained by interrupting the radiation at the entrance slit by a rotating shutter. Shutters of metal, mica, and sodium chloride are used to minimize the effect of scattered radiation. To adjust the frequency of the shutter to match the sharply tuned amplifier, the rotational speed of the shutter disk is controlled through a synchronous motor driven by a variable-frequency power supply. A thyratron-operated calibration flasher is used to put reference lines on the photographically recorded spectra. The housing in which the Nernst glower is mounted is equipped with windows so that it may be divided into compartments to serve also as a vapor cell. This unit carries a mounting designed to locate a liquid cell precisely.

INTRODUCTION

IN attempting to write a set of specifications for an infra-red spectrograph to be used as a research instrument upon which analytical methods may be developed and with which special problems may be solved, one is impressed by the large number of desirable features which are possessed, usually individually and not collectively, by instruments already constructed. Examples of such features follow: Randall and Strong[1] describe a spectrograph in which atmospheric absorption is removed by evacuation of the entire optical path, while Smith[2] uses a chemical method for this purpose. The use of sodium chloride and potassium bromide prisms as dispersing media is well known. More recently, Wright[3] has pointed out the superiority of lithium fluoride in the short wave regions. A spectrograph described by Gershinowitz and Wilson[4] permits the use of either of two prisms, while one described by Avery[5] allows choice among four prisms. Barnes, Gore, Liddel, and Williams[6] describe a spectrometer in which two

[1] H. M. Randall and J. Strong, Rev. Sci. Inst. **2**, 585 (1931).
[2] L. G. Smith, Rev. Sci. Inst. **13**, 54–62 (1942).
[3] N. Wright, Rev. Sci. Inst. **15**, 22–27 (1944).
[4] H. Gershinowitz and E. B. Wilson, Jr., J. Chem. Phys. **6**, 197–200 (1938).
[5] W. H. Avery, J. Opt. Soc. Am. **31**, 633–638 (1941).
[6] R. B. Barnes, U. Liddel, and V. Z. Williams, Ind. Eng. Chem. Anal. Ed. **15**, 662 (1943); R. B. Barnes, R. C. Gore, U. Liddel, and V. Z. Williams, *Infrared Spec-*

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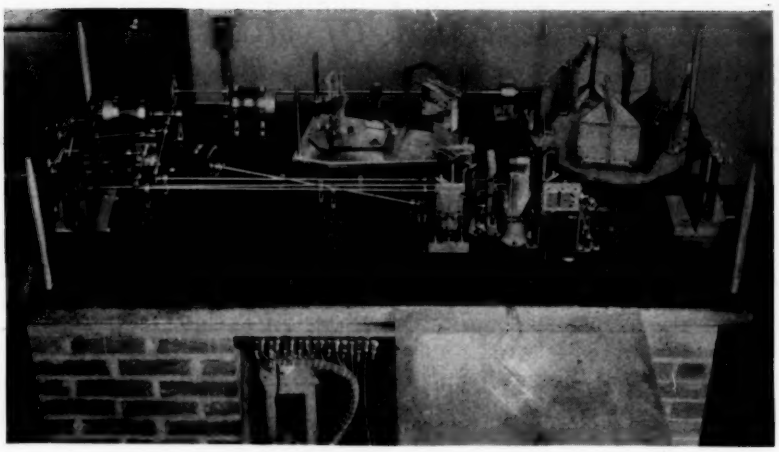

FIG. 1. Infra-red spectrograph with cover and large baffles removed. Relative positions of parts in this figure are the same as those in Fig. 2.

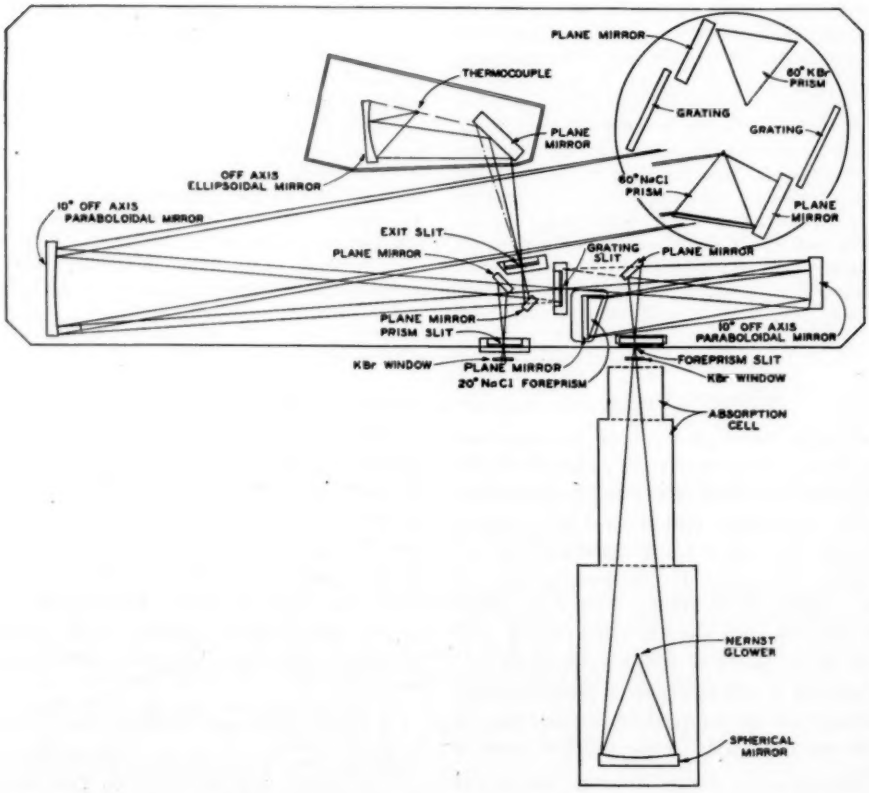

FIG. 2. Schematic diagram of optical arrangement of infra-red spectrograph and source housing.

prisms are used in series in a Littrow arrangement to give the dispersion of four prisms each used once. Brackett and McAlister[7] describe a spectrograph having a similar arrangement in which dispersion is obtained equivalent to that from four or five 60° prisms in series. An instrument used at E. I. duPont de Nemours and Company[8] is arranged so that either a prism or a grating may be used. Sleator[9] describes a grating spectrometer with a foreprism spectrometer in series with it. In a spectrograph described by Brattain,[10] "the prism is turned by a cam arrangement at such a rate that regardless of the variation of spectral slit width with prism position and regardless of the variation of actual slit width necessary to maintain constant energy, the prism turns through each spectral slit width in constant time." Various methods are employed for producing spectrograms on which either or both zero and 100 percent transmission levels are known.[4, 5, 10–12] These permit determination of percent transmission as a function of wave-length. A modification of the spectrograph originally described by McAlister, Matheson, and Sweeney,[13] makes it possible to record optical density directly.[14] These and many other possible features suggest the large number of choices which must be made in designing a research infra-red spectrograph.

There is presented here the description of a versatile infra-red spectrograph designed for use as a research instrument. Many of the most desirable features found in other instruments have been combined in it. To make it most useful in solving problems of various types, it has been made as flexible as possible. Convenience of operation has also been a major consideration. A summary of the characteristics of this instrument is to be found in the abstract, above.

troscopy—Industrial Applications and Bibliography (Reinhold Publishing Corporation, New York, 1944), p. 7.

[7] F. S. Brackett and E. D. McAlister, Rev. Sci. Inst. **1**, 181–193 (1930).

[8] J. R. Downing, private communication.

[9] W. W. Sleator, Astrophys. J. **48**, 125–143 (1918).

[10] R. R. Brattain, Phys. Rev. **60**, 164 (1941).

[11] E. B. Baker and C. D. Robb, Rev. Sci. Inst. **14**, 359–361 (1944).

[12] H. M. Randall, private communication.

[13] E. D. McAlister, G. L. Matheson, and W. J. Sweeney, Rev. Sci. Inst. **12**, 314 (1941).

[14] J. U. White, private communication.

The rapid-response evaporated thermocouple[15] and the sharply tuned vacuum tube amplifier[16] used with this spectrograph have been described previously.

SPECTROGRAPH OPTICS

Figure 1 is a photograph of the spectrograph with the cover removed. The positions of optical and mechanical parts may be seen in this figure. Figure 2 is a schematic diagram of the optics of the spectrograph and source housing. The relative positions of the optical parts are the same in these two figures.

In the prism spectrograph, the conventional optical arrangement employing a Littrow mirror is used. The radiation enters the spectrograph through the prism slit, seen in the center foreground of Fig. 1, and is deflected by a small plane mirror to the large off-axis paraboloidal mirror which has a focal length of 100 cm. This mirror is at the front left corner of Fig. 1. The collimated radiation traverses the prism and is returned by the plane (Littrow) mirror back through the prism to the large off-axis paraboloidal mirror. This mirror, with the aid of a second small plane mirror, forms a spectrum in the plane of the exit slit. The exit slit and the thermocouple are optically at the foci of an ellipsoidal mirror seen toward the rear center in Fig. 1. Since the focal lengths of the ellipsoidal mirror are 10 and 50 cm, the image formed on the thermocouple is reduced to one-fifth the size of the opening in the exit slit.

To use a grating as the dispersing element, the prism-grating table is rotated until the grating makes the proper angle with the collimated beam to return radiation of the desired wave-length to the exit slit. In order to prevent radiation of undesired orders from falling on the exit slit, a foreprism spectrometer, shown at the right front of Fig. 1, is used ahead of the grating spectrometer. Radiation enters the spectrograph through the foreprism slit. Provision is made for easily moving the source housing, which is described below, to a position in front of either the prism slit or the foreprism slit. The radiation is reflected from a small plane mirror to an off-axis parabo-

[15] L. C. Roess and E. N. Dacus, Rev. Sci. Inst. **16**, 164 (1945).

[16] L. C. Roess, Rev. Sci. Inst. **16**, 172 (1945).

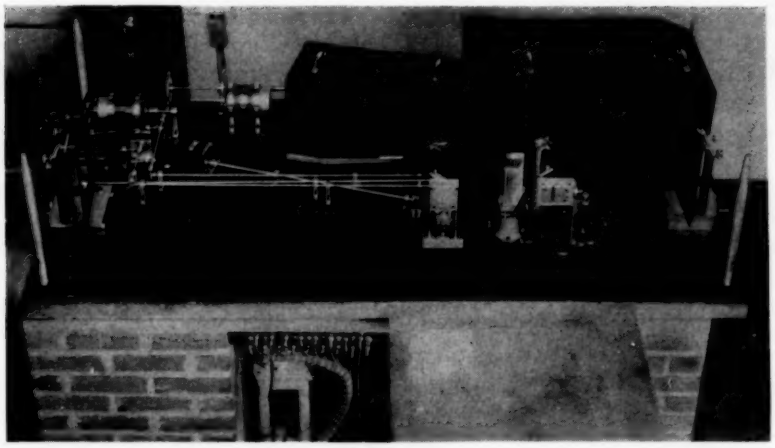

FIG. 3. Infra-red spectrograph with cover removed. All baffles are in place in this figure.

loidal mirror of 50-cm focal length which directs collimated radiation toward the foreprism. The 20° sodium chloride foreprism is backed by a plane (Wadsworth-Littrow) mirror. The radiation is returned to the small off-axis paraboloidal mirror which forms a spectrum of low dispersion on the grating slit. This slit is located optically at the same place as the prism slit. The plane mirror between the grating slit and the large off-axis paraboloidal mirror is on an elevator so that it may be moved out of the radiation path when the foreprism spectrometer is used.

The shift from a prism spectrograph to a foreprism-grating spectrograph or *vice versa* requires only three changes: (1) rotation of the prism-grating table; (2) lowering or raising of the elevator on which the plane mirror behind the prism slit is mounted; and (3) movement of the source housing so that radiation falls on the foreprism slit instead of the prism slit or *vice versa*. As will be discussed later, the first two changes are made by use of motors. The third change is made easy by mounting the source housing on ball-bearings which act as wheels and move on steel tracks provided with positive stops in the two positions. All changes can be made within a few minutes.

The prism, exit, and grating slits are all of identical construction except that the jaws of the first are curved. A description of these slits and of the foreprism slit, together with formulae for slit curvature, will be found elsewhere.[17]

In all infra-red spectrographs, it is necessary to install baffles to absorb or deflect radiation which would otherwise be scattered into the optical path and be detected by the thermocouple. Pieces of black velvet covering bright portions of holders on the prism-grating table and metal shields painted black and mounted on the two paraboloidal mirrors which may be seen in Fig. 1 serve as baffles. All other baffles may be seen in place on Fig. 3. The inside of the cover is painted flat black to minimize scattering of light falling on it. The amount of scattered radiation which is effective in increasing the amplifier output is further reduced through use of shutters made of appropriate materials. This is discussed below in connection with the source housing on which the shutter is located.

Figure 4 is a rear view of a typical mirror holder. The mirrors are rectangular in shape, the sizes being slightly greater than those required to make the prism or grating the aperture stop of the entire optical system. To permit maximum accuracy of adjustment, the entire mirror holder is mounted on a pair of tracks so that motion of the mirror along a line through its focal point is possible. Fine control of the motion along these tracks is obtained through use of a screw and nut

[17] H. M. Roemer and R. A. Oetjen, "Two Bilateral Spectrograph Slits," J. Opt. Soc. Am. (to be published soon).

which is located below the entire assembly. The conventional point-slot-plane support of the mirror backing plate is used. The three adjusting screws are arranged at the corners of a right triangle with one leg horizontal and one vertical. This permits rotation of the mirror about horizontal and vertical axes independently. This combination of fine adjustments, which is used on all important mirrors has the advantage that it permits continuous observation of changes in image appearance while changing a mirror position. In this way it is possible to make an alignment of the optical parts which one can be confident very closely approaches the optimum. It is essential that such a condition be reached, the penalty for failure to do so being loss of resolution.

The 60° sodium chloride and potassium bromide prisms have faces about 160 mm long by 110 mm high. The gratings used are replica gratings[18] having ruled surfaces about 150 mm long by 100 mm high, backed by glass plates of dimensions about 175 mm by 125 mm. Figure 5 is a portion of the 6-micron water vapor spectrum obtained with a sodium chloride prism. Figure 6 is a similar spectrum obtained using a replica grating having 3610 lines per inch. These spectrograms illustrate the wide range of resolving power available.

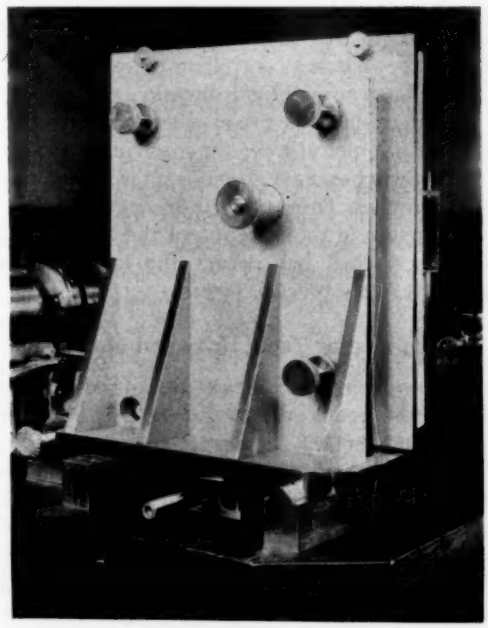

FIG. 4. Rear view of typical mirror holder. Tilting of mirror is accomplished by three adjusting screws at corners of right triangle having one leg vertical and one horizontal. A screw and nut below the assembly permits motion of the mirror along a line through its focal point.

[18] Obtained from Professor R. W. Wood, Johns Hopkins University, Baltimore, Maryland.

SPECTROGRAPH CASE

As is customary in evacuable spectrographs, the optical parts are mounted on a separate optical bedplate whose three legs rest on the main bedplate. Any deflection of the main bedplate caused by evacuation does not cause displacement of the parts on the optical bedplate relative to one another.

The spectrograph cover is fabricated from five sheets of $\frac{3}{4}$ inch steel welded together at the edges to form a box without a bottom. The main bedplate upon which the cover rests is the bottom. With this arrangement, removal of the cover gives maximum accessibility to all optical parts, and permits viewing them from the most advantageous angles during alignment.

All moving parts inside the spectrograph are controlled by motors located in the evacuated chamber. To bring power to these motors, 6L6 metal radio tubes (any metal tubes would be satisfactory), of which the elements and the upper portions of the envelopes have been removed, are soldered in holes through a plate which is bolted to the main bedplate. Copper

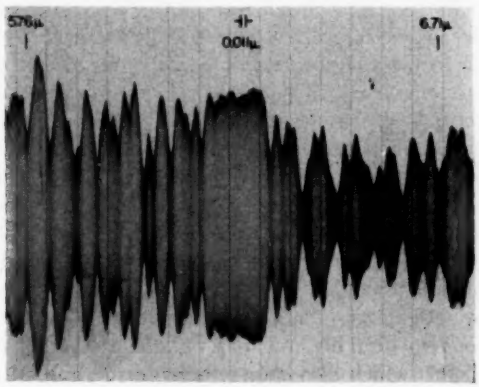

FIG. 5. A portion of the 6-micron atmospheric water vapor spectrum. Obtained with a sodium chloride prism.

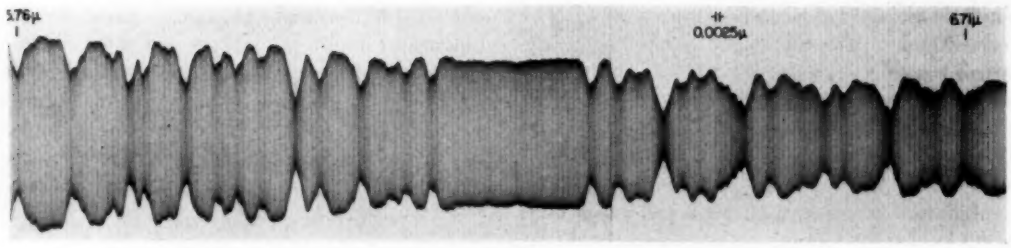

FIG. 6. A portion of the 6-micron atmospheric water vapor spectrum. Obtained with a replica grating having 3610 lines per inch.

wires soldered to the inside leads, and tube sockets slipped over the outside prongs in the ordinary way, serve as connectors. Each tube provides six leads which are well insulated from each other and from the bedplate, and which are positively vacuum tight.

Leaks which might occur around plates which carry electrical connectors, entrance windows, evacuation leads, or around the spectrograph cover, are prevented through the use of long pieces of solid rubber about $\frac{1}{8}$ inch in diameter which are cemented together at the ends. An alternative way of sealing the small space between spectrograph cover and bedplate is to put Apiezon "*Q*" around the outside. This is entirely satisfactory and is extremely convenient.

The pressure maintained in the spectrograph is of the order of 0.1 torr. A separate evacuation system is used to maintain a pressure of about 10^{-5} torr in the thermocouple housing.

MECHANICAL DRIVES

As has been stated, the movable parts inside the evacuated case are electrically controlled by motors. Induction and Autosyn types of motors are employed. This permits centralization of control of the spectrograph and associated apparatus in one unit. The fact that all controls are electrical makes it possible to locate this control unit anywhere with respect to the rest of the apparatus. It is mounted on a portable table, thus permitting the operator to change his location for carrying out different types of investigations. This has proved to be quite convenient. This unit may be seen at the left of Fig. 7, which also shows the spectrograph with its cover on and the source housing properly located before the foreprism slit.

Miscellaneous Drives

Separate induction motors located inside the evacuated case are used to control the width of the foreprism slit, the rotational position of the foreprism, and the vertical position of the plane mirror mounted on the elevator behind the prism slit. These motors and parts of the gear trains to the apparatus they are driving can be seen at the left side of Fig. 1. Revolution counters which are visible through a glass window in the spectrograph case indicate the positions of the units. The switches controlling these motors are located in the control unit mentioned above.

In these and other drives where damage could be done if a motor drove the mechanism too far, Micro Switches have been installed to act as limit switches. These prevent driving the mechanism further in the direction of the limit switch already reached but permit the motor to be operated in the reverse direction.

Prism-Grating Table Drive and Mounting

When prism spectra are being recorded, a typical rotational velocity for the prism-grating table is about 0.3 degree per minute. Grating spectra are recorded with the table rotating at a velocity about three times as great. A much faster speed is required in order to change from one prism to another or to a grating in a reasonable time. In order that this requirement for large changes in the speed of the prism-grating table may be conveniently satisfied from the control unit, an Autosyn system is used.

Essentially, an Autosyn system[19] consists of

[19] A more complete discussion of the operation of Autosyn systems is found in: S. Read, Jr. and E. W. Kellogg, J. Soc. Mot. Pict. Eng. **36**, 514 (1941).

two "motors" connected together electrically. One motor functions as a generator and is commonly called the master, while the other functions as a motor and is called the slave. If the shaft of the master is rotated by any means, the shaft of the slave will rotate in like manner. The mechanical analog of the electrical connection between the two units is a flexible shaft. In this installation the Autosyn master is located in the control unit and the Autosyn slave inside the evacuated case.

The Autosyn master is driven by a 1/75 hp synchronous motor through a gear train in which provision is made for changing gears to change the speed of the Autosyn. The Autosyn slave is connected to the prism-grating table through a permanent gear train. Thus, the speed of the prism-grating table is changed exactly as the gears between the drive motor and the Autosyn master are changed. The highest available speed of rotation of the table is about 14 degrees per minute. For obtaining spectra, interchangeable pairs of gears make it possible to rotate the table at nine speeds between 0.04 and 2.2 degrees per minute. Provision has also been made for automatically changing the speed while obtaining a spectrum so that spectra may be recorded with a linear wave-length scale. This mechanism has not yet been put into operation.

Because the coupling between the Autosyns is similar to that of a flexible shaft, there is a relative displacement between the two units which is dependent upon the load on the slave. Even though the load on the slave is quite constant, there are small variations in these relative displacements. If this introduces non-uniformity of rotation of the prism-grating table between adjacent recorded reference lines, errors are made in making wave-length measurements. To minimize non-uniformity of rotation of the table, the gear trains are designed so that a departure of the slave of about nine degrees from its correct position is required in order that the prism-grating table be one second from its proper position. Tests were made which show that the departure of the Autosyn slave from its proper position is always less than nine degrees. Since under conditions of unusual loads it is possible for the Autosyns to get one or more whole revolutions out of phase, one revolution counter is located inside and another outside of the spectrograph. Failure of these counters to show the same reading indicates that such slip has taken place. Provision is made so that such a slip may be readily corrected.

The use of Autosyn systems in this drive and another discussed below has proved to be satisfactory in every respect. As well as eliminating the troublesome connections where moving parts enter the evacuated chamber, it has also provided flexibility not possible with rigidly connected driving systems. It is believed that this is a novel way of controlling movement in an infra-red spectrograph.

The last gear in the train from the Autosyn slave is a large bronze worm wheel mounted on the shaft supporting the prism-grating table. A glass-hard worm is in contact with this worm wheel. Teeth on the worm and wheel are spaced 0.1 inch apart. The worm wheel has 504 teeth, hence the pitch diameter is about 16 inches. After the hobbing of the worm wheel, a soft iron worm identical with the glass-hard worm was made. Fine lapping compound was put between the soft iron worm and worm wheel and lapping

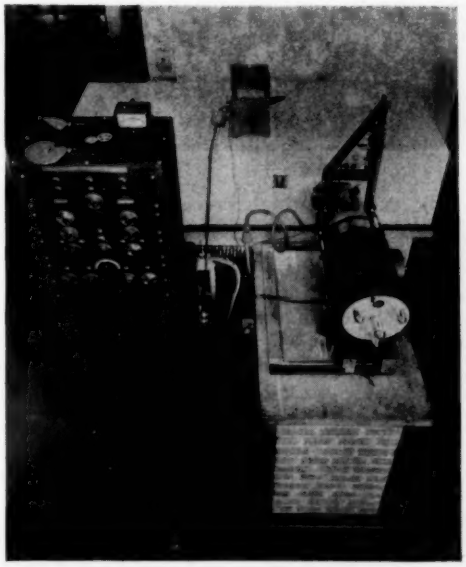

FIG. 7. Infra-red spectrograph with cover in place. Source housing, at right, is in position in front of the fore-prism slit. Cabinets at left contain mechanism for controlling spectrograph and associated equipment.

was carried on for several days by driving the worm at fairly high speeds with a motor. Finally, the glass-hard worm was put in place and run in with the worm wheel, a layer of oil being used between the worm and worm wheel. All of the lapping was done with the worm and worm wheel in their proper places on the spectrograph. This procedure assures that the shape of the teeth of the worm wheel is as near as possible to that of the worm and that the relative positions of these two parts are correct.

It will be observed that this use of a worm wheel makes it possible to rotate the prism-grating table through the entire 360 degrees and to use any portion for the slow speed required in obtaining a spectrum. Thus if it should appear desirable to replace and rearrange the elements on the prism-grating table, the driving mechanism need not be changed in any detail. This is a real advantage over many of the devices, used in other spectrographs, which permit rotation of the table through only a few degrees.

The prism-grating table is mounted on a shaft supported by a pair of SKF 6209 preloaded ball bearings separated by spacers $2\frac{1}{4}$ inches long. These bearings, which have the large preload of 900 pounds, can be used only at very slow rotational speeds (e.g., three r.p.m.) without danger of introducing excessive heat. According to engineers of SKF Industries, Inc., tests have shown this to be the arrangement of ball bearings which has a minimum amount of both radial and axial play.

The extremely high precision methods which were used in making the worm and worm wheel, and in mounting the driving mechanism having to do with the rotation of the prism-grating table, are demanded by the necessity of being able to reproduce settings of the prism-grating table to within a few seconds of arc. For example, on the circumference of the worm wheel, one second of arc corresponds to about 0.00004 inch.

Slit Drive

As is the general practice, the widths of the openings of the entrance and exit slits are always maintained equal when obtaining spectra. Since either the prism slit or the grating slit may act as the entrance slit of the prism or grating spectrometer, this means that the openings in all three slits must be maintained equal. This is most conveniently accomplished by making these three slits of identical construction insofar as is possible, and driving them from a common drive.

In order to obtain a constant signal-to-noise ratio throughout the entire spectrum, since all sources of noise are independent of the signal, the gain of the thermocouple output amplifier should be maintained at a fixed value and the slit widths should be continuously varied to provide a constant thermocouple output as the spectrum is traversed. In addition to maintaining a constant signal-to-noise ratio, this would permit direct recording of percent transmission if a linear amplifier were used or of optical density if a logarithmic amplifier were used. This assumes, of course, that there is no scattered radiation, a condition which does not exist in spectrographs described up to the present time, including the present one. In this spectrograph, although the results obtained show that the ideal of having a perfectly constant thermocouple output throughout the spectrum has not been attained, a considerable advance has been made over the procedure of taking of spectra in steps and changing slits manually between steps.

The slit-controlling mechanism is located in the control unit. As in the prism-grating table drive, an Autosyn system is employed and a permanent gear train connects the Autosyn slave to the slits. The drive is unlike the prism-grating table drive in that no provision has been made for changing gears in the train connecting the 1/150 hp slit-drive synchronous motor to the Autosyn master. Therefore, the slit-drive synchronous motor always rotates the same amount to change the slit widths by one micron. In this case, the Autosyn system is used, not to permit changing the speed of the slit mechanism inside the evacuated case, but to permit coordination of the slit width with the position of the prism-grating table. This coordination is effected through a servomechanism which controls the operation of the slit drive motor.

The servomechanism, which is located in the control unit, operates as follows: The rotational position of a suitably shaped cam is coordinated with the position of the prism-grating table. A cam follower having one of a pair of electrical

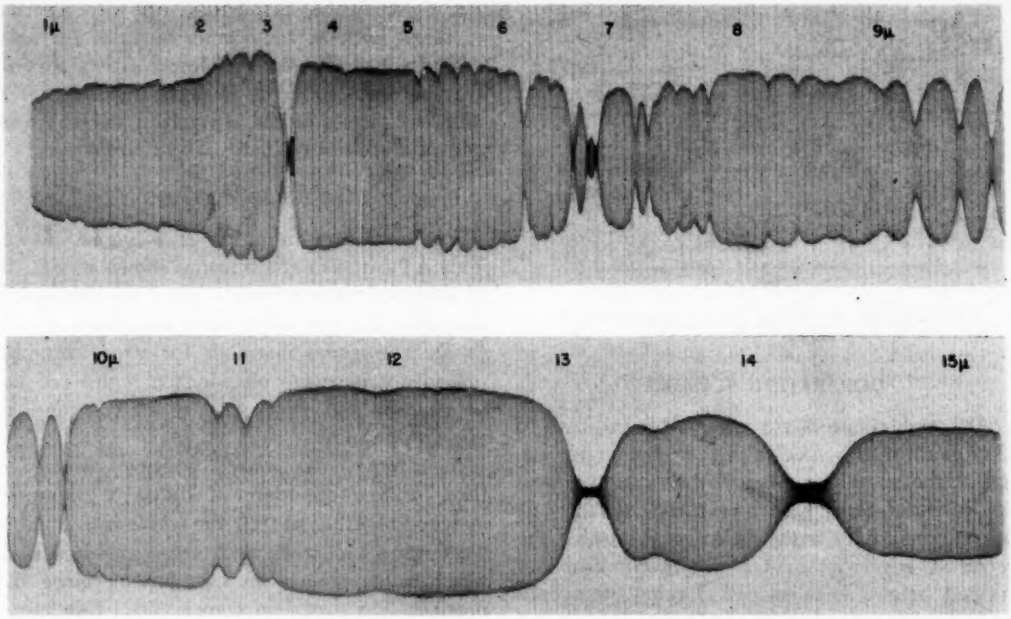

FIG. 8. 1–15 micron spectrum of API-NBS liquid isopropylbenzene. Sample thickness about 25 microns. Purity 99.95±0.02 percent. Obtained with a sodium chloride prism. Slit widths varied automatically.

contacts attached to it is held against the cam by a spring. The other electrical contact is mounted on a rack in a gear train driven by the slit drive motor, hence is directly coordinated with widths of the openings in the slits. These electrical contacts are in the control circuit of a patented electronic reversing switch known as a Motron.[20] When the contacts open, the slit drive motor is rotated in the direction to close them, and when the contacts close, the direction of the motor is reversed. Thus, the Motron tends to cause the slit widths to vary about a mean value determined by the radius of the cam at the point in contact with the follower. Actually the "hunting" is less than the backlash in the various gear trains, so that when obtaining a spectrum, the changes in slit widths are unidirectional and stepwise. The sizes of the steps are small relative to the widths of the openings except when the openings in the slits are extremely small, such as when the sodium chloride prism is used in the three-micron region. As in the case of the prism-grating table drive, two revolution counters are used so that any slip between the Autosyns may be detected and remedied. These counters indicate the widths of the slit openings in microns. The effectiveness of this slit-controlling mechanism may be seen in Fig. 8, which shows the sodium chloride spectrum of liquid isopropylbenzene from 1 to 51 microns, obtained through use of automatically controlled slit widths.

[20] Electronics **15**, 128 (October, 1942).

RECORDER

Photographic recording is used. The recording mechanism is located in a darkroom adjoining the spectrograph room. This permits keeping the spectrograph room lighted normally even when recording. The camera is close to the photographic chemical trays, so that processing of the spectrograms is convenient. The motor which drives the recorder is controlled from the control unit. Through the use of rotary switches having several positions and many circuits, it is possible to start the recorder, turn on the recording lamp, and start the spectrograph, all in one operation.

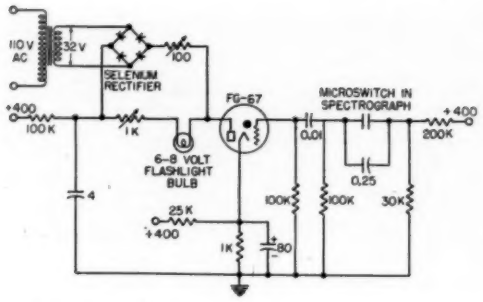

FIG. 9. Circuit diagram of the thyratron-operated calibration flasher.

CALIBRATION FLASHER

Although counters are provided to indicate to the operator the spectral region being investigated, the actual wave-length calibration of any record is not dependent upon these counters but on reference lines made an integral part of the recorded spectrogram by the mechanism described below. A brass disk having 30 evenly spaced teeth around its circumference is mounted on the end of the shaft which drives the large worm wheel under the prism-grating table. A Micro Switch is so mounted that as each tooth passes it, the switch is closed. Each time the switch closes, a lamp in front of the cylindrical lens of the camera is flashed. One tooth is filed down so that it does not operate the Micro Switch. Thus, every thirtieth reference line is missed. These missed lines serve to identify the remaining lines.

The circuit diagram of the calibration flasher is shown in Fig. 9. The Micro Switch fires a thyratron FG-67 which discharges a 4-μf condenser through the lamp. In this way, the magnitude and duration of the current pulse passed through the lamp is independent of the length of time of closure of the Micro Switch. It is desirable that this be so because of the wide range of speeds used in recording spectra which would otherwise cause wide variations in the intensity and width of the recorded reference lines. Although the charge passing through the lamp was always the same, when flashed very frequently the lamp did not have time to cool between flashes so that brighter flashes were produced. To overcome this, a small direct durrent is passed through the lamp at all times. For convenience, a selenium full-wave rectifier in series with a transformer is used. An alternating current is not completely satisfactory for this purpose since the flashing pulses occur at different phases of the alternating current wave and produce lines which vary in intensity.

SOURCE HOUSING

The source of radiation is a Nernst glower. This is located in the housing shown in Fig. 10. In addition to providing a place for the source, the assembly has three other functions. It acts as an absorption chamber for vapor samples, provides a platform on which a liquid cell can be placed, and supports the shutter and its associated motor.

Essentially, the source housing consists of three hollow cylinders of different diameters fastened together so that the whole is evacuable. This unit is mounted on a rectangular steel plate which is supported on legs having large ball bearings which run on tracks permitting movement between positions in front of the two

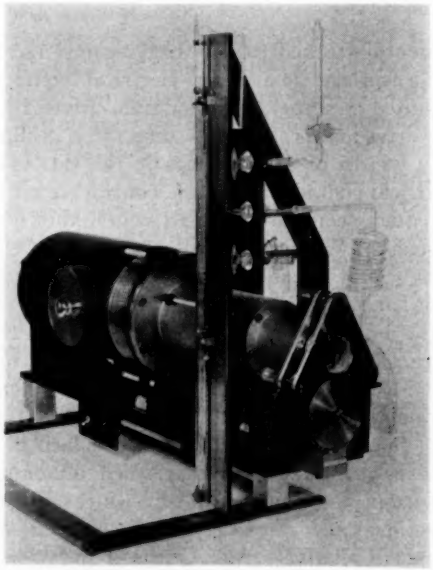

FIG. 10. Source housing assembly for infra-red spectrograph. The source and its mirror are at the rear end. A window at the center permits use of the front end for a vapor absorption cell. A gas handling system is attached to this cell. A liquid cell is in place at the front end of the unit. A mica shutter is in front of the liquid cell.

entrance windows in the spectrograph. A large Sylphon bellows installed in the housing permits reducing to a minimum the air path between the source housing and the entrance window on the spectrograph.*

The Nernst glower is mounted 20 cm from a spherical mirror of 16-cm focal length. This mirror, which is at the far end of the source housing, as shown in Fig. 10, forms an enlarged image of the source on the prism or foreprism slit 80 cm away. This large image will fill a slit whose opening is several millimeters wide. This location of the source near the focal point of the mirror makes it possible to have a long vapor cell. As Sawyer[21] makes clear, the power per unit solid angle entering the spectrograph is independent of relative positions of source, mirror, and slit if an image of the source is formed on the slit.

Cells and Gas Handling System

The end of this unit toward the entrance slit serves as a vapor absorption cell. A potassium bromide window divides the housing into a sample chamber and a source chamber. This permits admitting inflammable vapors to the sample chamber without danger due to the presence of the incandescent source. Windows may be located at either of two places inside the cell so that 100- or 400-mm path lengths are available, or these windows may be left out altogether. The latter condition is used when investigating liquid samples. The source and cell ends of the unit are separately evacuable by independent connections to a vacuum pump.

The gas handling system consists of several glass stopcocks and a closed-end mercury manometer provided with a vernier so that pressures can be read to 0.1 torr. The stopcocks are arranged so that interconnections may be made between the pump, manometer, absorption cell, and any type of a sample container. Because the Sylphon bellows permits motion of the cell relative to the gas handling system, the connection between the two consists of a long piece of glass tubing bent in the form of a helix. Both ends of the helix are equipped with ground tapered joints so that ample flexibility is provided by the system.

In order to determine the extent to which the absorption cell is evacuated, a thermocouple vacuum gauge has been installed. This is useful in providing information relative to the freedom of the cell from leaks.

A platform at the nose end of the source housing locates and supports the liquid cell. Samples in the solid phase may also be placed on this platform. The triangular plates seen in Fig. 10 are part of a liquid cell in its normal place.

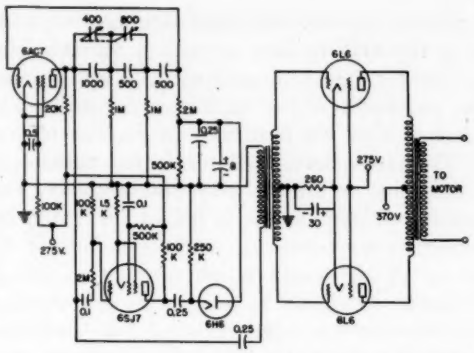

FIG. 11. Circuit diagram for the phase-shift oscillator and power amplifier for the shutter motor.

Shutter Drive

The vacuum tube amplifier[16] used with this spectrograph is sharply tuned, hence the radiation beam must be interrupted at the center frequency of the pass band of the amplifier. A segmented rotating disk which serves as a shutter is shown in place on the front of the source housing in Fig. 10. In order to chop the radiation beam with exactly the proper frequency, a synchronous motor driven by a variable-frequency power supply is used. The circuit diagram for the phase-shift oscillator and power amplifier for the shutter motor are shown in Fig. 11. The phase-shift oscillator is the standard type described by Ginzton and Hollingsworth.[22] The oscillator frequency is varied by use of the variable air

* *Note added in proof.* Recently it has been found desirable to enclose the space between the source housing and the entrance window and stream dry nitrogen through, in order completely to eliminate atmospheric absorbing materials from the optical path.

[21] R. A. Sawyer, *Experimental Spectroscopy* (Prentice-Hall, Inc., New York, 1944), pp. 37–40.

[22] E. L. Ginzton and L. M. Hollingsworth, Proc. I.R.E. **29**, 43 (1941).

condenser shown. The 6SJ7 amplifier together with the 6H6 rectifier provide a variable bias voltage for the 6AC7 oscillator, thus maintaining the amplitude of the oscillation approximately constant over the frequency range. The output of the phase-shift oscillator is fed through a transformer to the 6L6 push-pull amplifier. The power amplifier output is fed to the 1/150 hp condenser start-and-run synchronous motor by means of an output transformer. The 2.65-μf condenser originally in series with one winding of the motor was replaced by a 1.5-μf condenser as the latter gave more constant voltage with change of frequency. The frequency stability of the phase-shift oscillator has been found to be ample after a short warm-up period.

Shutter Materials

By making the shutters out of the proper materials, the amount of scattered radiation which contributes to the recorded signal can be reduced. Shutters have been used for this purpose on several instruments at the University of Michigan[23] for a number of years. The shutter is made of material which is opaque to radiation of the wave-length region being investigated and is transparent to the more intense short wave regions. Since the scattered radiation which could cause trouble is of the shorter wave-length transmitted by the shutter, it is not interrupted with the frequency which the amplifier passes, hence it has no effect on the output of the amplifier. A shutter made of mica, which is opaque for radiation whose wave-length is longer than about 9.5 microns and transparent to radiation of shorter wave-lengths, is used to investigate the spectral region between 10 and 18 microns and is shown on Fig. 10. The use of a metal shutter for investigations at wave-lengths shorter than 10 microns and a mica shutter for the remainder of the region covered by the sodium chloride prism reduces scattered radiation to less than two percent when investigating spectral regions whose wave-lengths are less than 12 microns and to about ten percent at 15 microns. A shutter with sodium chloride plates is used for determining spectra in the region of wave-lengths longer than about 17 microns.

[23] H. M. Randall and F. A. Firestone, Rev. Sci. Inst. **9**, 404 (1938); R. A. Oetjen, C. L. Kao, and H. M. Randall, Rev. Sci. Inst. **12**, 515 (1942); A. Adel, private communication.

ACKNOWLEDGMENTS

The author is indebted to Professors Harrison, M. Randall, and Ernest F. Barker of the University of Michigan for major contributions to the design, and to his colleague, Dr. Louis C. Roess, who contributed extensively throughout the development of this apparatus. He wishes to make special acknowledgment of the excellent workmanship as well as design contributions of Mr. Hermann Roemer and his men in the University of Michigan Physics Department Instrument Shop, without which this apparatus could never have taken its present form.

Alternating-Current Bolometer for Infra-Red Spectroscopy

C. H. SCHLESMAN* AND FRANK G. BROCKMAN**
Research and Development Division, Socony-Vacuum Oil Company, Incorporated, Paulsboro, New Jersey

(Received July 13, 1944)

An alternating-current bolometer system has been developed for detecting and recording radiant energy in infra-red spectroscopy. Almost constant use over a ten-months' period dictates certain improvements which are pointed out. The useful sensitivity is limited now by fluctuations originating in the power supply to the bolometer bridge.

IN his theory of the alternating-current bolometer, Parry Moon[1] points out the advantages of this system compared with the direct-current bolometer and the thermocouple as detectors of radiant energy. Moon and Mills[2] tested the theory but to our knowledge no attempt, previous to the one reported here, has been made to develop the system for use as a detector for infra-red spectroscopy.[3]

The following describes this development. The description is divided into four sections treating the bolometer, the bolometer bridge, the amplifier-recorder, and the bridge power supply.

THE BOLOMETER

The production and the properties of the nickel bolometer filaments are described in another article.[4] The bolometer and mounting described there were designed to fit into a brass case which is supplied with a rocksalt window.

THE BOLOMETER BRIDGE

Because the bridge is supplied with alternating current, shielding of the bridge is necessary and was incorporated as shown in the bridge circuit diagram given as Fig. 1.

As is customary in direct-current bolometer systems, the bolometer described above was constructed with two filaments as nearly identical as possible so that, when incorporated into the bridge circuit, the ratio of the resistances of these two filaments would remain constant regardless of ambient temperature changes and changes in bridge current. The detection of radiant energy is effected by allowing the radiation to fall upon only one of the two filaments, thereby changing this ratio. If the effects of ambient temperature changes and current changes are not eliminated, the result is instability, manifested as fluctuations and drift.

The expedient of the bolometer pair, however, has achieved only a first-order compensation since it has not been possible to construct two filaments of identical resistances. Additional compensation has been obtained by incorporating the non-inductive manganin resistors R_V and R_T. Fluctuations in the voltage supplied to the bridge, and therefore in the current through the

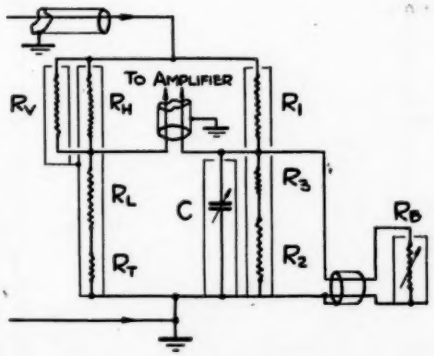

FIG. 1. Bolometer bridge.

R_1, R_2 25.00 ohms R_3 1.43 ohms
R_D 6-dial decade box, 11,111.1 ohms
R_V Voltage compensating resistor, 414 ohms
R_T Temperature compensating resistor, 2.50 ohms
R_H Bolometer filament with higher resistance
R_L Bolometer filament with lower resistance
C Balancing capacitor, 350 mmf max.

* Director, Research and Development Division, Socony-Vacuum Oil Company, Incorporated.

** Now with the Richmond Hill Laboratories of the North American Philips Company, Incorporated, Dobbs Ferry, New York.

[1] Parry Moon, J. Frank. Inst. 219, 17 (1935).

[2] Parry Moon and W. R. Mills, Jr., Rev. Sci. Inst. 6, 8 (1935).

[3] E. Lehrer, Zeits. f. tech. Physik 18, 393 (1937), has described a bolometer system which uses alternating-current amplification. This system, however, differs in principle from the one described here. In that described by Lehrer, modulation of the bolometer output is obtained by periodically interrupting the radiation entering the spectrograph.

[4] Frank G. Brockman, J. Opt. Soc. Am., to be published.

filaments, are compensated, at any one current, by the resistor R_V. The value of this resistor was determined experimentally as the one which gave the minimum unbalance of an initially balanced bridge upon the application of a small increment in bridge supply voltage. The resistor R_T is necessary to compensate the bridge for ambient temperature changes. This value of resistance was calculated to provide the arm R_L+R_T with a temperature coefficient of resistivity equal to the coefficient of the parallel combination of R_V and R_H. The experimentally determined temperature coefficients of the two bolometer filaments were used in this calculation. The resistor R_3 was inserted so that bridge balance could be achieved with about 5000 ohms in R_B. At this value R_B has sufficient range to yield perfect balance, and the switch contact resistance is negligible compared with 5000 ohms.

It has been found that two factors are involved in the voltage compensation. If the voltage applied to the bridge is changed and the bridge is rebalanced after equilibrium has set in (a period of a few minutes), the curve marked "Equilibrium" in Fig. 2 is obtained when the bridge voltage is plotted against the balancing resistor R_B. If, on the other hand, the bridge is set in balance at any one voltage and the voltage is quickly altered by some small percentage, a practically instantaneous deflection of the balance indicator may occur which will be followed by the slower drift to the equilibrium position. The magnitude of this instantaneous deflection in arbitrary scale units was determined for the bridge in equilibrium at various input voltages, using a constant and small (about 0.05 percent) percentage change in the input voltage. The results of these tests are recorded as the "Instantaneous" curve of Fig. 2. Note that the deflections change sign and go through zero. As the instrument is now functioning, it appears, therefore, that one has two choices of operation: the first at about 1.45 volts r.m.s. input, at which slow drifts in the power supply are compensated, and the second at about 1.61 volts r.m.s., at which rapid fluctuations of the power supply are compensated.

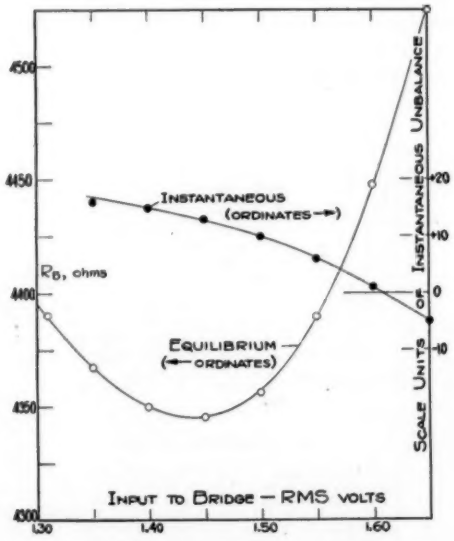

FIG. 2. Bridge balance—input voltage.

It will be noted that this behavior is observed with the bolometer sealed off in air at atmospheric pressure, which suggests an explanation of the effect. It is possible that the instantaneous change is due to the heating of the bolometer ribbons (which are very rapid in their response) while the slower secondary effect may be due to the heating of the air surrounding the filaments. The equilibrium temperature of the gas undoubtedly will be different from the instantaneous temperature of the ribbons. An obvious test of the correctness of this explanation is to evacuate the bolometer enclosure, and, if the explanation is correct, then operation under high vacuum is probably a means of bringing the two possible operating points together, with a major improvement in operation. This test is planned as soon as the demands on the spectrograph as an analytical tool have fallen to a level which will release the instrument for further experimentation.

THE AMPLIFIER-RECORDER

The circuit diagram[5] of the amplifier inserted between the output of the bridge and the recorder is given as Fig. 3. Full-scale sensitivity at maximum gain is 0.13 microvolt when operated into a high speed recorder with a 15 ohm input resistance and a full scale of 7.5 millivolts. The resonance curves of this amplifier are reproduced in Fig. 4.

[5] Tuning by a bridged T network in the inverse feed-back circuit was described by H. H. Scott, Proc. I. R. E. **26**, 226 (1938).

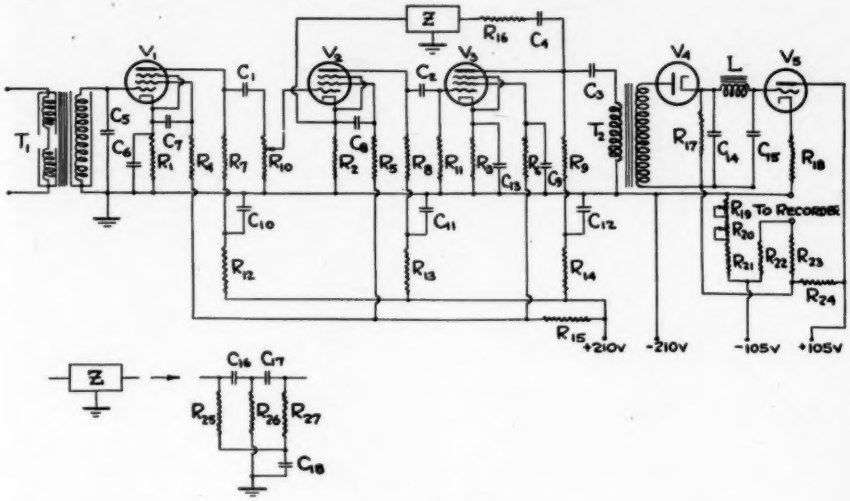

FIG. 3. Amplifier.

R_1, R_2, R_3	2200 ohms	C_1, C_2, C_3	0.003 mf.
R_4, R_5, R_6	1.5 megohms	C_4	0.1 mf.
R_7, R_8, R_9, R_{11}	0.5 megohm	C_5	0.024 mf.
R_{10}, R_{11}	1.0 megohm	C_6, C_{10}, C_{11}, C_{12}, C_{13}	2.0 mf.
R_{12}, R_{13}, R_{14}, R_{16}	0.1 megohm	C_7, C_8, C_9	0.05 mf.
R_{17}	2.0 megohms	C_{14}	0.05 mf.
R_{18}	5,000 ohms	C_{16}, C_{17}	0.00300 mf.
R_{19}	10 ohms	C_{18}	0.00600 mf.
R_{20}	100 ohms	T_1	Shielded, tuned secondary, turns ratio 1:30
R_{21}	100 ohms	T_2	Turns ratio 1:3
R_{22}	200 ohms	L	700 henries
R_{23}	5000 ohms		
R_{24}	25,000 ohms		
R_{25}, R_{27}	53,000 ohms		
R_{26}	26,500 ohms		

V_1, V_2, V_3 Type 1221
V_4 6H6, diodes in parallel
V_5 6J5
All heaters supplied with 6.3 v, 60 cycles.

The noise in the amplifier has been studied by disconnecting the input transformer and connecting the grid of the first stage to ground through various resistances. Knowing the r.m.s. voltage sensitivity of the amplifier, the noise voltage was determined for these resistances. The practical thermal noise voltage equation for room temperature, $\langle V_T^2\rangle_{Av}=1.64\times10^{-20}(R-R_o)F$, can be used with the data obtained in this manner by plotting $\langle V_T^2\rangle_{Av}/1.64\times10^{-20}$ against R, where $\langle V_T^2\rangle_{Av}$ is the mean square thermal noise voltage, R_o is the equivalent input resistance for the noise originating in the first tube, R is the resistance introduced into the grid circuit, and F is the band width in c.p.s. for ½ voltage gain at resonance. The graph given as Fig. 5 was obtained in this way. The slope of the straight line is equal to F and is found to be 84 c.p.s., which agrees well with the band width of this part of the amplifier as determined directly (Fig. 4). The equivalent

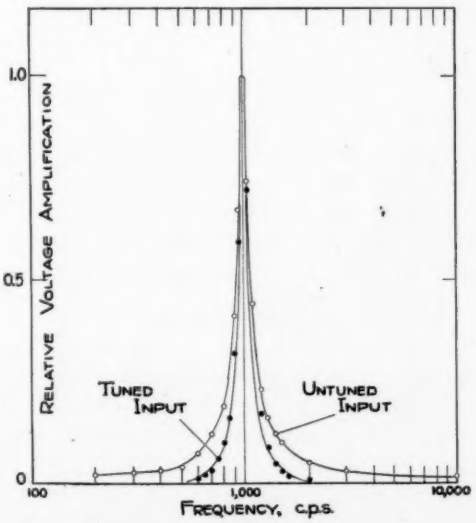

FIG. 4. Amplifier resonance curves.

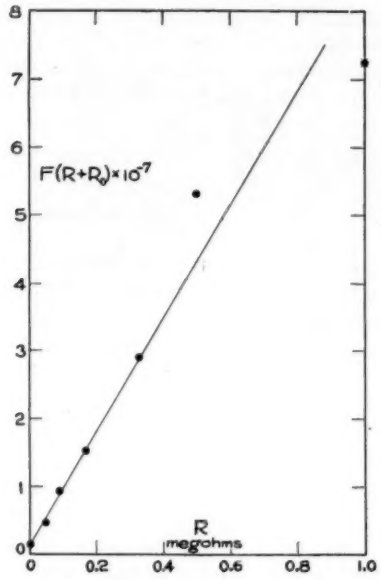

FIG. 5. Noise study of amplifier.

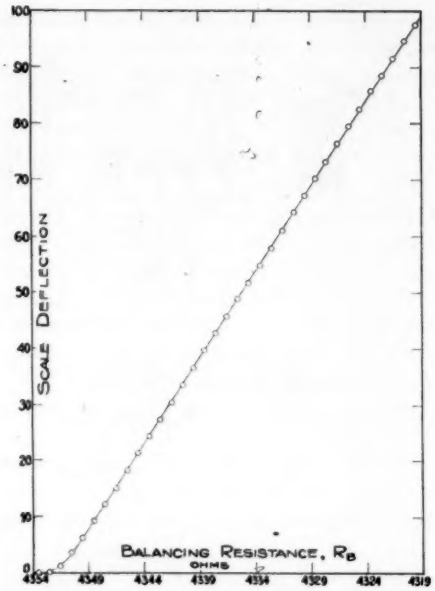

FIG. 6. Linearity of bridge, amplifier, and recorder.

noise resistance of the first tube, 14,000 ohms, is obtained from the intercept which is R_oF. With a 30:1 step-up ratio input transformer and an input resistive source of 25 ohms, the equivalent source resistance on the grid of the first tube is 22,500 ohms, so that if the amplifier can be utilized at full gain the limit is not the noise of the first tube but the thermal noise of the source.

In addition to the advantage in thermal noise reduction, a tuned amplifier is necessary to discriminate against the harmonics of the fundamental 1000 cycles. The bolometers are harmonic generators since their time constant is of the same order of magnitude as that of the period of the bridge power frequency.

Plate supply power is obtained from two regulated d.c. supplies of the usual type.

Since no alternating-current recorders are available, the amplified 1000-cycle current must be rectified to supply a direct-current recorder. The output rectifier is followed by a degenerative direct-current amplifier to match the high output resistance of the rectifier to the low input resistance of the recorder.

In recording the unbalance of the bolometer bridge, two choices of method exist: The recorder may indicate the magnitude of the unbalance voltage or the recorder may be so constructed that the bridge is maintained in balance and the recorder would then indicate the resistance

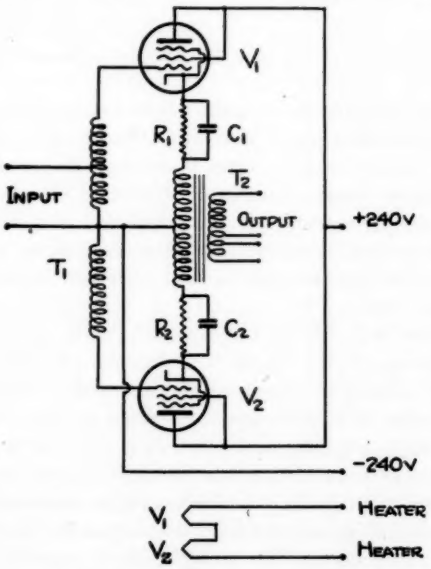

FIG. 7. Degenerative power amplifier.

T_1 Thordarson T74A31 T_2 UTC S15
R_1, R_2 1000 ohms C_1, C_2 1 mf.
V_1, V_2 6G6G

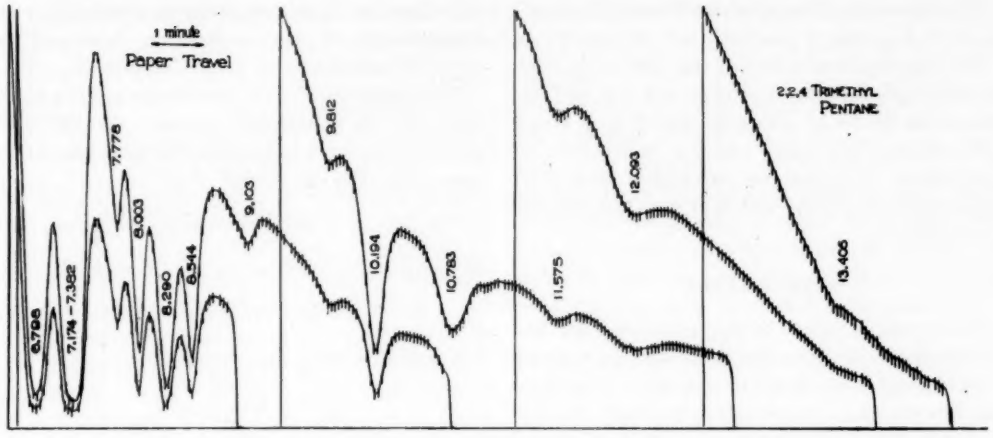

FIG. 8.

change necessary to maintain balance. The former was used here because such a recorder is an article of commerce, whereas the latter recorder would be a special item.

The operation of any bolometer system is based on the principle that the resistance change of the bolometer filament is directly proportional to the amount of radiant energy which it receives. That the amplifier-rectifier-recorder is linear in resistive unbalance of the bridge is illustrated by the curve in Fig. 6 which was obtained when the bridge was placed out of balance by the resistor R_B in Fig. 1. The following data pertain to Fig. 6. The resistance R_B shunts R_2+R_3 (26.43 ohms). Over the range $R_B=4354$ to 4319 ohms, the parallel combination is linear in R_B to better than 1 part in 10^6, and a 5-ohm change in R_B corresponds to a 0.00018-ohm change in the parallel combination. At, for instance, 4339 ohms for R_B, the nominal resistance of the parallel combination is 26.26998 ohms. The scale is linear except for about 4 percent of the scale at the zero end. This non-linearity is eliminated by placing the bridge out of balance by R_B by about 8 percent without radiant energy upon the bolometer. Subsequent unbalance produced by radiation upon the bolometer is then recorded as deflection above this "zero."

The response time of the system is limited by the response time of the amplifier-rectifier unit. This is so because of the filter network between the rectifier and the d.c. amplifier. This filter was interposed to smooth out rapid fluctuations which originate in the power supply to the bridge. The response time of the over-all system is about 0.8 second to attain e^{-1} times the full deflection.

BRIDGE POWER SUPPLY

As pointed out in the description of the bolometer bridge, the balance of the bridge is very sensitive to variations in the input voltage. Although the bridge has been compensated for such variations, the compensation is not complete and the other expedient of maintaining the input voltage constant is also practiced. For this constant voltage supply, a General Radio Company Type 723-A 1000-cycle vacuum-tube fork has been altered, and the battery supply has been replaced by power from a high stability regulated d.c. power supply. This power supply is patterned after the one described by Miller,[6] and tests made upon it show that the stability is better than 7 millivolts in 240 volts over periods as long as a half-hour.

The 1000-cycle power available from the vacuum-tube fork is not sufficient to supply the bolometer bridge, so that a highly degenerative power amplifier (Fig. 7) follows the fork. Heater and plate power for this amplifier are taken from the regulated d.c. power supply used to supply the fork.

[6] S. E. Miller, Electronics **14**, 27 (November, 1941).

The harmonic content of this 1000-cycle power source is less than ½ percent.

The amplitude stability of this fork and power amplifier combination has been studied and the short-time (5 to 10 minutes) stability is about 0.01 percent. The fork, however, is sensitive to temperature changes and exhibits a slow drift presumably caused by the heat developed in the fork enclosure.

PERFORMANCE

A permanent record of the spectrum from 2 to 14 microns can be obtained in 40 minutes without recourse to a photographic procedure in recording. The region (7 to 14 microns) usually studied in hydrocarbon mixtures is recorded in 24 minutes. These times include partial rescanning at slit width changes.

Figure 8 is a reproduction of a recorded spectrum. The short lines superimposed are wavelength reference marks. The rate of paper speed is marked on the record.

The useful sensitivity is now limited by the fluctuations originating in the power supply to the bridge. The gain of the amplifier, therefore, is reduced to a full-scale sensitivity of 1.1×10^{-6} volt, or 2.6×10^{-6} volt, depending on the region of the spectrum investigated. An improvement in the performance of the power supply and/or in the compensation of the bridge, as pointed out above, can be expected to extend the useful sensitivity.

From the data in Fig. 6 (taken at a full-scale amplifier sensitivity of 13×10^{-6} volt) and from the resistance-temperature characteristics of the bolometer, it is possible to show that, at the present useful sensitivity (corresponding to 1.1×10^{-6} volt), full-scale deflection of the recorder corresponds to a change in temperature of the bolometer of 11×10^{-4} degree C. Assuming that the minimum detectable change is 0.01 of full scale, the minimum detectable temperature change is at present 11×10^{-6} degree C.

It is possible to increase the useful sensitivity with a sacrifice in speed of response by increasing the damping of the amplifier to average out the fluctuations. In our application, however, the speed of response is of prime importance.

The sensitivity of the bolometer may be calculated in the following manner. At 25°C the conductance of a bolometer filament can be expressed by the equation,[4]

$$C=Co-AI^2, \tag{1}$$

or the power dissipated in the filament is

$$P=I^2/C=Co/AC-1/A. \tag{2}$$

For a small change in conductance

$$\Delta P=-\frac{Co}{AC^2}\Delta C=\frac{Co}{A}\Delta R. \tag{3}$$

From the data used in Fig. 6, a change of 0.0013 ohm in one arm of the approximately equal arm bridge produces a voltage change of 13×10^{-6} volt at the output of the bridge. With this value of ΔR and $Co=0.05$ and $A=7.2$ (both from reference 4), ΔP is calculated to be 9.0×10^{-6} watt. The surface area of the bolometer upon which radiation falls is 0.053 sq. cm., so that the equivalent radiation per sq. cm. is 1.7×10^{-4} watt per sq. cm. This energy produces an output voltage of 13×10^{-6} volt, and the sensitivity is therefore 0.076 v/watt/sq. cm. The only assumption made in this calculation is that the blackened surface of the bolometer is 100 percent absorbing. The foregoing sensitivity refers to the bolometer in air at atmospheric pressure. It is in good agreement with an experimentally determined value of 0.055 v/watt/sq. cm. based on the wattage input to a frosted glass tungsten incandescent lamp used as a source. In comparing this value with others it should be recalled[1] that the sensitivities of thermocouples are frequently computed on the basis of the open circuit e.m.f. and that when so computed the practical sensitivity is halved when operated into a galvanometer under the condition of maximum energy transfer. The bolometer sensitivity reported here is the useful sensitivity.

An Improved Screening Test for Red-Green Color Deficiency Composed of Available Pseudo-Isochromatic Plates

LOUISE L. SLOAN*
Army Air Forces School of Aviation Medicine, Randolph Field, Texas
(Received October 8, 1945)

TESTS of color vision composed of pseudo-isochromatic plates provide a very simple and rapid means of classifying large numbers of individuals as either normal or color deficient. For this purpose the ideal test is one in which normal individuals make relatively few errors, and the range of error scores of color deficient subjects is sharply differentiated from that of normal subjects. The extent to which a given group of charts fulfills this requirement will depend upon the number of charts composing the test and upon the diagnostic efficiency of each. Fewer charts are needed if those selected have a relatively high efficiency. The essential data needed for the evaluation of individual charts are the rates of misclassification of normal and color deficient subjects; i.e., the percentage of normal individuals failing and the percentage of color deficient individuals passing each chart.

Collins,[1] in 1937, published data on the rates of misclassification of the charts composing the fifth edition of the Ishihara test. The subjects were classified as color deficient, borderline normal, and normal on the basis of a battery of color vision tests. Data on the same charts have been published recently by Hardy, Rand, and Rittler.[2] A somewhat similar study of the individual plates of the American Optical Company test was made at the AAF School of Aviation Medicine in 1942 in which the Ishihara test was used to classify the subjects as normal or color deficient. A number of the American Optical Company charts were found to have a very high rate of misclassification of normal subjects; there were likewise many charts with a high rate of misclassification of color deficient subjects. An abridged test consisting of 17 of the better charts was shown in this study to provide a much more definite means of differentiating normal and color deficient subjects than does the complete test. In 1944 this 17-plate test was adopted by the Army Air Forces as the basic color vision test. An adjunctive test is used to measure the degree of defect of those who fail the basic test. Gallagher, Gallagher, and Sloane[3] have also recommended an abridged version of the American Optical Company charts. In their selection, emphasis was placed chiefly on the elimination of charts failed by normal subjects. Still another abridged version of this test composed of 12 plates is used by the Royal Canadian Air Forces.[4] The criteria for selection were similar to those used in 1942 by the AAF School of Aviation Medicine in that misclassification of color deficient as well as of normal subjects was considered undesirable. All but one of the 12 plates in the Canadian test are included in the 17 plates adopted by the Army Air Forces. In an attempt to reduce the misclassification of subjects by individual charts, the U. S. Navy developed 36 new plates in which modifications were made in the choice of confusion colors, formation of digits, etc. A limited edition of this test was produced and issued for experimental study in 1945.

Since the American Optical Company supplies three very similar color vision tests for the RCAF, the U. S. Navy, and the U. S. Army Air Forces, respectively, adoption of a single test composed of plates produced by this company and satisfactory to all three organizations would be desirable. In order to prevent previous memorization of the charts by applicants, it is advisable to reserve one test for the sole use of

* On leave of absence from the Wilmer Ophthalmological Institute of the Johns Hopkins University and Hospital, 1942–1945.

[1] M. Collins, "Tests in Common Use for the Diagnosis of Colour Defect," Nature **140**, 532, 569 (1937).

[2] L. H. Hardy, G. Rand, and M. C. Rittler, "Tests for the Detection and Analysis of Color Blindness. I. The Ishihara Test: An Evaluation," J. Opt. Soc. Am. **35**, 268 (1945).

[3] J. R. Gallagher, C. D. Gallagher, and A. E. Sloane, "A Critical Evaluation of Pseudo-Isochromatic Plates and Suggestions for Testing Color Vision," Yale J. Biol. and Med. **15**, 79 (1942).

[4] John V. V. Nicholls, Sqn/Leader, "RCAF Colour Plate Test." Report to Associate Committee on Aviation Medical Research, National Research Council, Canada.

TABLE I. Scores of atypical group compared with those of normal and color deficient subjects.

	Point of reversal Anomaloscope	Errors 13 plates of Rabkin test	Score Color threshold tester[a]
Normal subjects	100% +1.0 to −1.0	100% 0 to 2	97.5% 60 to 64
Color deficient subjects	97.4% greater than 1.0	97.5% 6 or more errors	92% less than 60
"Atypical" color deficient subjects			
G.C.	0.0	3, 5	64, 62, 64
H.W.	0.0	8	63, 63
W.S.	0.0	8	64, 64, 64
C.M.	+3.0	3	62
C.J.C.	+2.5	5	64

[a] Louise L. Sloan, "A Quantitative Test for Measuring Degree of Red-Green Color Deficiency," Am. J. Ophth. **27**, 941 (1944).

the various Armed Forces and, if possible, to have another for the use of ophthalmologists, medical examiners in industry, etc.

PRESENT INVESTIGATION

The chief purpose of this study was to obtain data on the diagnostic efficiency of the individual charts published by the American Optical Company and from these results to select charts to form a new test. For comparison, data on the diagnostic efficiency of charts from other tests were also obtained.

The 273 subjects were first classed as normal or color deficient on the basis of other color vision tests, either an anomaloscope test,[5] the Rabkin Polychromatic Plates, or both. In doubtful cases both of these tests and other color vision tests were given. Two hundred subjects were classified as normal, 68 as color deficient. Five were classed as "color deficient, atypical," either because of low error scores on the Rabkin test or because of normal responses on the anomaloscope. Table I gives the scores of each subject on the three color vision tests, and, for comparison, data on normal and color deficient subjects based on findings reported elsewhere.[6]

[5] Louise L. Sloan, "The Eastman Color Temperature Meter Used as an Anomaloscope," J. Opt. Soc. Am. **34**, 618 (1944).

[6] Louise Sloan Rowland, "Selection of Color Vision Tests for the Army Air Forces: A Review of Studies Made at the AAF School of Aviation Medicine." AAF School of Aviation Medicine Project No. 393, Report No. 1 (1 June 1945).

Note. Louise L. Sloan. The author's married name is used in reports of the AAF School of Aviation Medicine because of Civil Service Regulations.

The 273 individuals, after classification by other tests, were examined with the 17-plate AAF test and the 36-plate Navy test. Each chart was exposed for five seconds. Spontaneous correction of errors was permitted but the response was scored as passing only if a perfectly correct answer was given within the specified time limit. In the occasional instances in which both figures were seen on a chart of the dual response type, the answer was scored on the basis of the figure seen more clearly. Either a Macbeth Daylight Lamp or a desk lamp equipped with a Daylight Fuorescent tube was used to illuminate the charts. Approximately one-half of the normal subjects and one-half of the color deficient subjects were tested using the Macbeth Daylight Lamp; the fluorescent lamp was used for the remainder of the group. Analysis of the results with each type of illumination revealed that the error scores of normal and of color deficient subjects were essentially the same for the two types of illumination. In the presentation of the

TABLE II. Distribution of error scores.

	AAF 17 plates			Navy 36 plates			Rabkin 13 plates		Dvorine 11 plates	
No. of errors	200 *N*	73 *D*	68 *D-A*	200 *N*	73 *D*	68 *D-A*	104 *N*	408 *D*	100 *N*	47 *D*
0	143			12			72		32	
1	40			39			30		43	
2	14			35			2		21	
3	3			42				1	2	
4		1	1	27				3	2	
5		0	0	25				6		1
6		3	1	12				3		0
7		2	1	6				11		1
8		3	1	0				17		4
9		3	3	1	1			17		9
10		0	0	1	1			36		15
11		5	5		0			73		17
12		1	1		0			153		
13		1	1		1	1		88		
14		5	5		0	0				
15		5	5		1	0				
16		9	9		1	0				
17		35	35		0	0				
18					0	0				
19					2	1				
20					0	0				
21					1	1				
22					2	2				
23					2	2				
24					4	4				
25					4	4				
26					1	1				
27					2	2				
28					2	2				
29					7	7				
30					2	2				
31					10	10				
32					12	12				
33					8	8				
34					6	6				
35					1	1				
36					2	2				
Aver. no. of errors	0.39	14.3	14.9	3.0	28.3	29.5	0.33	11.2	0.99	9.8

N = Normal
D = Color deficient
D-A = Color deficient excluding 5 atypical cases

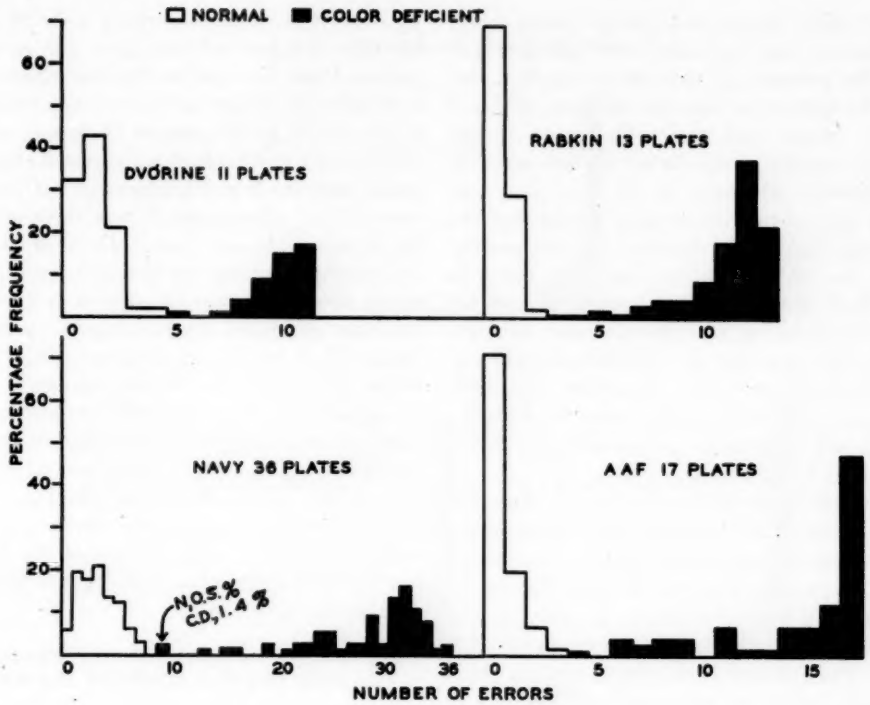

FIG. 1.

data, therefore, the results obtained in the two types of artificial daylight have been combined.

Table II gives the distribution of error scores on the AAF and Navy tests of the 200 normal and 73 color deficient subjects. The corresponding values obtained when the five atypical cases are omitted from the color deficient group are also shown. The same table shows, for comparison, similar data for other normal and color deficient individuals who were tested with 13 charts of the Rabkin test[7] and with 11 charts of the Dvorine* test.[8] The efficiency with which each of the four tests separates normal and color deficient subjects may be more easily compared in the graphs of Fig. 1. These graphs show the percentage of normal subjects and the percentage of color deficient subjects making each score. It may be seen that, although the average error scores of the two groups differ markedly in all four tests, the scores of a few color deficient subjects differ only slightly from the scores of a few normals, and in the case of the Navy test there is an actual overlap with two of each group making 9 and 10 errors.

The 5 color deficient subjects classed as "atypical" because of their performances on other tests all made relatively few errors on the AAF and Navy tests. It seems probable, therefore, that the wide range in the error scores of color deficient subjects is in part caused by actual differences in color perception rather than by defects in the charts. Inspection of the responses to individual plates reveals, however, that in each test there are certain charts which are more frequently failed by normal subjects

[7] E. B. Rabkin, *Polychromatic Plates for Testing Color Vision* (Ukrainian Ophthalmic Institute, 1939), second edition.

* The complete Rabkin test contains 18 testing charts. Those omitted in this study are two charts for testing yellow-blue blindness, two which are failed only by those with the protanopic type of red-green color deficiency, and one which is failed only by those with a marked deficiency for red and green. Only 11 of the 60 Dvorine charts were used because preliminary studies indicated that only these charts show any evidence of especial difficulty for the color deficient subject.

[8] Israel Dvorine, "A New Diagnostic Method of Testing and Training Color Perception," Am. J. Optom. and Arch. Am. Acad. Optom. **21**, 225 (1944).

than are other charts, and certain charts which are relatively easy for many color deficient subjects. The presence of such charts tends to decrease the separation between the error scores of the two groups and their elimination should therefore produce a significant improvement in the diagnostic efficiency of the test. The percentage (Q_N) of normal subjects failing and the percentage (Q_D) of color deficient subjects passing each of the AAF and Navy charts are given in Table III. Values of Q_D were computed both for the entire group of 73 color deficient subjects and, for the same group, with the omission of the 5 atypical cases. For comparison with these misclassification rates similar data for Rabkin, Dvorine, and Ishihara pseudoisochromatic plates are given in Table IV.

The values of Q_N for the 17 charts of the AAF test range from 0 to 11 percent. The values of Q_D when the 5 atypical cases are omitted range from 1.5 to 23.6 percent. For the 36 Navy charts Q_N ranges from 0 to 69.5 percent, Q_D (for typical color deficient subjects only) from 0 to 61.9 percent. Thirty-seven of the 53 charts, however, have values of Q_N not exceeding 3.5 percent and an equal number have values of Q_D not exceeding 16 percent. A majority of the Rabkin charts likewise have low misclassification rates, but there are a few charts with relatively high values of Q_N or Q_D. Plate No. 8, for example, is failed by 27 percent of normal subjects who frequently read it as an *S* instead of a 5. Plate No. 11 is apparently an inefficient chart since 58 percent of color deficient subjects give the correct response. Plate No. 4 of the Dvorine series, though it is failed by almost all color deficient subjects, is also failed by 58 percent of normal subjects. The figure 8 in this chart is composed of blue and green dots on a red background. If the green dots are not distinguished from the background the figure will be seen as a 3. The normal subject can distinguish both the blue and green portions of the figure, but may also read it as a 3 because the blue and green portions may be judged too dissimilar to form a single figure. Chart No. 52 of the Dvorine test, a brown figure on a green background is read correctly by 40 percent of color deficient subjects, which suggests that they can detect a difference in brightness or in saturation, if not in hue. Data published by Collins[1] in 1937 and more recently by Hardy *et al.*[2] show similarly that the fifth edition of the Ishihara test includes a few plates having relatively high misclassification rates.

SELECTION OF AN 18-PLATE TEST FROM AMERICAN OPTICAL COMPANY PLATES

Methods of obtaining a single index which will rate charts in accordance with their relative diagnostic efficiencies from the values of Q_N and Q_D have been developed by Green and Sloan.[9] These methods were applied in the present study to select plates of high diagnostic efficiency from those distributed by the American Optical Company. Although some of the Dvorine and Rabkin

TABLE III. Percentage rates of misclassification.

17 AAF plates			17 USN plates corresponding to AAF series			19 USN plates remaining		
200	73	68	200	73	68	200	73	68
N	*D*	*D-A*	*N*	*D*	*D-A*	*N*	*D*	*D-A*
0.0	11.0	10.3	1.5	11.0	7.4	0.0	48.0	44.1
11.0	6.9	4.4	0.0	11.0	7.4	3.5	31.6	29.4
3.0	8.2	7.4	6.0	2.7	2.9	0.0	63.0	61.9
7.0	8.2	7.4	0.5	9.6	5.9	0.0	61.6	59.0
0.5	19.2	16.2	0.0	55.0	51.6	1.0	30.2	28.0
1.5	27.4	23.6	7.5	11.0	8.8	0.0	17.8	11.8
2.5	8.2	7.4	0.0	13.7	10.3	1.0	20.6	16.2
2.5	20.6	17.7	0.0	38.4	33.9	3.5	6.9	4.4
0.0	24.6	20.6	0.0	50.7	48.6	1.0	12.3	5.9
2.5	13.7	11.8	0.0	41.1	36.8	13.5	9.6	4.4
0.0	17.8	11.8	20.5	2.7	1.5	0.5	12.3	7.4
1.0	13.7	8.8	3.5	15.1	13.2	2.0	8.2	1.5
0.0	6.9	1.5	16.5	1.4	1.5	8.0	1.4	0.0
1.0	12.3	7.4	30.0	1.4	1.5	69.5	0.0	0.0
1.0	20.6	16.2	0.0	12.3	7.4	23.0	5.5	1.5
0.0	28.8	23.6	0.0	24.0	19.1	8.5	11.0	4.4
5.0	12.3	10.3	18.5	0.0	0.0	1.5	5.5	1.5
						31.5	49.4	48.6
						27.0	59.0	57.4

N = Normal
D = Color deficient
D-A = Color deficient excluding 5 atypical cases

TABLE IV. Percentage rates of misclassification.

	Rabkin 13 plates			Dvorine 11 plates			5th edition Ishihara test			Hardy, Rand, & Rittler	
Plate no.	104 *N*	408 *CD*	Plate no.	100 *N*	47 *CD*	Plate no.	286 *N*	Collins 45 *CD*		32 *N*	74 *CD*
3	1.0	7.6	2	2.0	12.7	2	0	40		0	42
4	0.0	26.0	3	3.0	5.5	3	0	21		0	46
5	2.9	2.9	4	58.0	1.8	4	1	12		0	0
6	0.0	7.6	16	2.0	10.9	5	44	0		22	0
7	0.0	1.5	21	0.0	7.3	6	1	0		13	5
8	26.9	0.25	22	4.0	3.6	7	0	5		0	12
9	1.0	8.1	23	2.0	10.9	8	0	5		0	8
10	0.0	6.6	24	18.0	3.6	9	0	2		6	18
11	0.0	58.4	35	8.0	0.0	10	9	0		13	9
14	1.0	1.5	36	1.0	3.6	11	28	0		16	4
15	0.0	18.3	52	1.0	40.0	12	1	5		3	11
16	0.0	13.7				13	0	10		3	20
17	0.0	27.0									

[9] Earl L. Green and Louise L. Sloan, "Two Criteria for the Selection of Color Vision Test Plates," J. Opt. Soc. Am. **35**, 723 (1945).

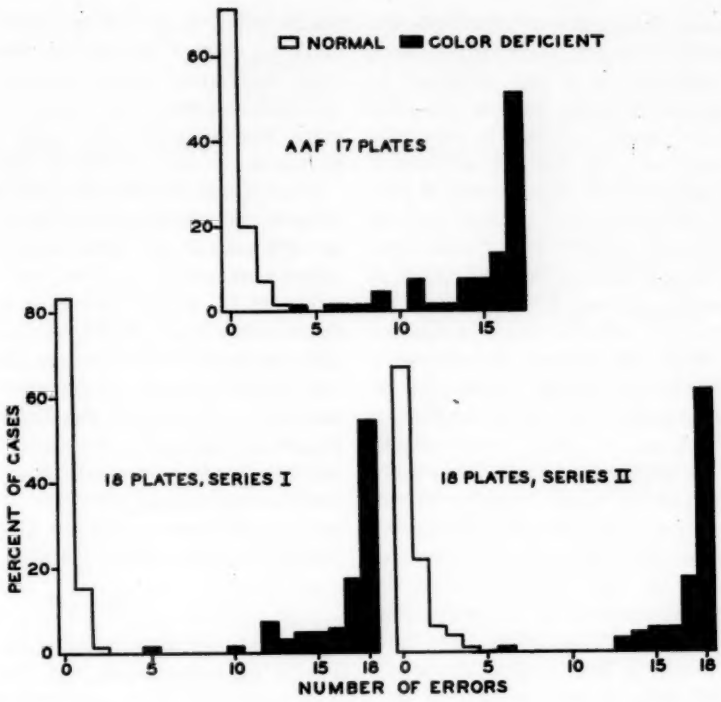

FIG. 2.

plates would probably be rated as highly efficient, they were not considered for the following reasons. Charts of the Dvorine type are employed by their author in training procedures believed by him to improve color vision, and therefore, might be less efficient when used to test subjects who had previously had such training. The Rabkin charts provide many auxiliary clues which could be used in memorizing the correct responses if these plates were more widely distributed. Consequently, while, the choice of colors appears to be excellent, the format of the plates should be modified.

TABLE V. Distribution of error scores.

No. of errors	AAF 17-plate test 200 N	5 A	68 D	18-plate test Series I $k=1/5$ 200 N	5 A	68 D	18-plate test Series II $k=1$ 200 N	5 A	68 D
0	143			167			134		
1	40			31			44		
2	14			2			12		
3	3				2		8	1	
4			1*		0		2	0	
5			0		0	1*		1	
6		2	1		1	0		0	1*
7		1	1		0	0		0	0
8		2	1		0	0		0	0
9			3		1	0		1	0
10			0		1	1		1	0
11			5			0		1	0
12			1			5			0
13			1			2			2
14			5			3			3
15			5			3			4
16			9			4			4
17			35			12			12
18						37			42
Aver. no. of errors	0.39	7.0	14.9	0.18	6.2	16.6	0.55	7.6	17

* Aviation Cadet who may have memorized some American Optical Company charts.

N = Normal
A = Color deficient, atypical
D = Color deficient

Eighteen plates with the highest diagnostic efficiency were selected from those comprising the AAF and Navy tests. Since 17 of the latter are modifications of the original American Optical Company charts used in the AAF test, only one of a pair of similar charts was chosen when both showed a satisfactory diagnostic efficiency. Two separate groups of 18 charts were chosen. For Series I the values of Q_D were multiplied by a weighting factor, known as the importance ratio, of $k=1/5$. In selecting Series II equal importance was given to values of Q_N and Q_D.

An importance ratio smaller than unity is used

if correct responses from color deficient subjects are less undesirable than are incorrect responses from normal subjects. In a test designed to classify individuals as either normal or color deficient, the ideal situation is that in which the average error score of color deficient subjects is close to the maximum and that of normal subjects close to zero. It may be argued that the second of these requirements if of greater importance since errors among normal subjects suggest that something other than color discrimination is being tested, whereas correct responses from color deficient subjects can be attributed to individual differences in color discrimination. If an appropriate weighing factor is applied, a selection of plates can be made which should give a low average error score for normal subjects although at the cost of some reduction in the average error score of color deficient subjects.

The distribution of error scores given by the two selections of 18 plate tests is shown in Table V for comparison with the corresponding data for the 17-plate AAF test. The same data are shown graphically in Fig. 2. The data apply to the same 268 subjects used in determining the misclassification rates. The 5 atypical subjects have error scores on all three tests differing only slightly from normal. It is probable that no selection of available charts will provide a marked differentiation of this group from the normal group. When atypical subjects are excluded it is found that the two 18-plate tests give a far better differentiation between normal and color deficient subjects than does the 17-plate AAF test. Series I ($k=1/5$) may be considered preferable to Series II ($k=1$) because of the very low frequency of errors among normal subjects, only 1 percent of whom make more than one error. These findings indicate that incorrect responses due to causes other than poor color discrimination have been almost entirely eliminated in the selection of charts for Series I.

It should be emphasized that the distribution of error scores has been determined from the data for 200 normal and 73 color deficient subjects which were used in the first place to compute the values of Q_N and Q_D. While it is very probable that another group of 200 normal subjects would give essentially similar results, this assumption is less valid in the case of the color deficient group because of the smaller number of subjects and the greater variability among color deficient than among normal individuals. Further studies are therefore planned in which the present AAF test and the 18-plate test (Series I) will be given to additional color deficient subjects.

SUMMARY

Data are presented giving the percentage of normal subjects failing and the percentage of color deficient subjects passing individual pseudo-isochromatic plates. Charts from the Rabkin and Dvorine color vision tests as well as those produced by the American Optical Company were studied. The latter included the 17 plates composing the Army Air Forces color vision test and 36 plates developed for the use of the Navy. The methods developed by Green and Sloan are applied in selecting 18 of the best charts. This group of charts is shown to provide a highly efficient test for the differentiation of normal and color deficient subjects.

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On the MacAdam Ellipses

ALEXANDER W. WUNDHEILER

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1. PROBLEM AND ANSWER

HYPOTHESES about the distribution of the axes of the MacAdam ellipses[1] in length and direction can be verified only if the errors in these quantities are known. These errors can be derived from the error involved in the determination of the radii of these ellipses. We shall refer to the ellipses determined by MacAdam as to the *average* ellipses, and denote the relative error in their radii by p. If a and b are the semi-axes of the average ellipse, consider two homothetic ellipses of semi-axes, respectively $a(1-p)$, $b(1-p)$ and $a(1+p)$, $b(1+p)$. The strip between these two ellipses contains all the other ellipses fitting the experimental data. It will be our problem to determine (1) the maximum of the angle between the major axes of an acceptable ellipse and the corresponding average one; (2) the extreme values of the ratio of these major axes, and of the corresponding minor axes.

The problem could be also stated as follows: The radii of an ellipse suffer changes not exceeding p times the radius. How much can the major axis be tilted, and what is the maximum change in the lengths of the axes?

We shall obtain the following answer:

(1) The maximum angle θ is given by

$$\sin 2\theta = 4p/(1-p^2)(e^2/(1-e^2)^{\frac{1}{2}}) = 4p/(1-p^2)ef,$$

where e is the eccentricity of the average ellipse, and $f=e/(1-e^2)^{\frac{1}{2}}$.

(2) For a given θ the extreme values of the ratio x of the squares of the major axes are given by the roots of the equation (we put $\beta=\sin\theta$)

$$(1+f^2\beta^2)x^2-2(1+p^2)x+(1-p^2)^2(1-e^2\beta^2)=0,$$

and the corresponding ratio y for the minor axes by

$$(1-e^2\beta^2)y^2-2(1+p^2)y-(1-p^2)^2(1+f^2\beta^2)=0.$$

At maximum θ these equations have double roots, and we obtain

$$x=(1+p^2)/(1+f^2\beta^2), \quad y=(1+p^2)/(1-e^2\beta^2).$$

(3) For θ freely variable the extreme values of both axes ratios are $1-p$ and $1+p$.

2. NOTATIONS AND AUXILIARY FORMULAS

We consider two concentric ellipses: the average one and another acceptable one. The quantities relative to the latter will be marked with a prime.

a, a'; b, b'; r, r' are, respectively, the major semi-axes, the minor semi-axes, and two collinear radii of the two ellipses.

$c^2=a^2-b^2$; $c/a=e$, $c/b=f$. Note the useful relations: $e^2+e^2f^2=f^2$, $ef=f/e-e/f$.

$x=(a'/a)^2$, $y=(b'/b)^2$, $z=(r'/r)^2$.

$\theta=$angle between the major axes of the two ellipses. $\alpha=\cos\theta$, $\beta=\sin\theta$.

$\xi=1-e^2\beta^2$, $\eta=1+f^2\beta^2$, $\sigma=ef\alpha\beta$. Note: $\xi\eta=1+\sigma^2$, $e^2\eta^2+f^2\xi^2=e^2+f^2$.

$m=\eta x+\xi y$, $n=xy$. $u=(1-p)^2$, $v=(1+p)^2$.

$\phi=$angle between the variable radius and the major semi-axis of the other acceptable ellipse. The angle of the same radius with the major semi-axis of the average ellipse is $\phi-\theta$. $\lambda=\cos\phi$, $\mu=\sin\phi$.

3. THE EXTREME VALUES OF THE RADII RATIO

Let the common center be the pole, and let the major axis of the other ellipse be the polar axis. Then the polar equations of the two ellipses are

$$r^2[b^2\cos^2(\phi-\theta)+a^2\sin^2(\phi-\theta)]=a^2b^2$$

and

$$r'^2[b'^2\cos^2\phi+a'^2\sin^2\phi]=a'^2b'^2.$$

Hence, in the notations introduced,

$$(r'/r)^2=z=n\frac{b^2(\lambda\alpha+\mu\beta)^2+a^2(\lambda\beta-\mu\alpha)^2}{b'^2\lambda^2+a'^2\mu^2},$$

or, arranging by powers of λ and μ,

$$[b'^2z-n(b^2\alpha^2+a^2\beta^2)]\lambda^2-2nc^2\alpha\beta\lambda\mu+[a'^2z-n(a^2\alpha^2+b^2\beta^2)]\mu^2=0.$$

[1] David L. MacAdam, "Visual sensitivities to color differences in daylight," J. Opt. Soc. Am. **32**, 247–274 (1942).

The ratio λ/μ must be real and $a' \geq b'$; these are the only conditions to be satisfied by θ, x and y. Consequently the discriminant of the last equation must be non-positive:

$$[b'^2z - nb^2(1+f^2\beta^2)][a'^2z - na^2(1-e^2\beta^2)] - n^2c^4\alpha^2\beta^2 \leq 0,$$

or dividing by $a'^2b'^2$, expanding and making use of our notations,

$$z^2 - mz + n \leq 0. \tag{1}$$

Only those values of θ, x, y are possible for which this inequality has solutions satisfying the conditions $u \leq z \leq v$. For this it is necessary and sufficient that

$$m^2 - 4n \geq 0, \tag{2}$$

$$u^2 - mu + n > 0, \quad 2u < m, \tag{3}$$

$$v^2 - mv + n > 0, \quad m < 2v. \tag{4}$$

This follows easily from an inspection of the graph of $w = z^2 - mz + n$ in the plane (z, w). The roots of Eq. (1) are the extreme values of z.

4. SOLUTION OF THE INEQUALITIES

We compute first

$$m^2 - 4n = \eta^2x^2 + 2(\xi\eta - 2)xy + \xi^2y^2.$$

The discriminant of this quadratic form is $\xi^2\eta^2 - (\xi\eta - 2)^2 = 4(\xi\eta - 1) = 4\sigma^2$, which is positive, except for the degenerate case $\sigma = 0$ (that is, $\theta = 0$ or $\theta = \pi/2$ or $c = 0$). Thus $m^2 - 4n$ is, for every x and y, positive or zero, and inequality (2) is satisfied always. ($m^2 - 4n = 0$ corresponds with an ellipse homothetic with the average one.)

To solve the two inequalities (3), note that

$$u^2 - mu + n = (x - u\xi)(y - u\eta) - u^2\sigma^2.$$

In the plane (x, y) the last expression is positive (or zero) outside of the center-containing region of the equilateral hyperbola whose center is at $(u\xi, u\eta)$, and whose real axis is parallel to the first bisectant. Consider now the inequality $m > 2u$. The straight line $m = 2u$ does not intersect the preceding hyperbola in the plane (x, y). In fact, substituting $m = 2u$ into $u^2 - mu + n = 0$, we get $u^2 = n = xy$, and substituting $y = u^2/x$ into $m = \eta x + \xi y = 2u$, we obtain $\eta x^2 - 2ux + \xi u^2 = 0$, an equation whose discriminant $u^2(\xi\eta - 1) = u^2\sigma^2$ is positive (or zero, in the degenerate case), and which, consequently, has no roots. $m > 2u$ is the region above the line $m = 2u$. The common solution of the inequalities (3) is therefore the region above the upper branch H_u of our hyperbola.

Similarly, the solution of the inequalities (4) is the region below the lower branch H_v of the hyperbola $(x - v\xi)(y - v\eta) = v^2\sigma^2$. Finally:

The common solution of the inequalities (2), (3), (4), for a given θ, is given in the (x, y) plane by the region H between, respectively, the upper branch H_u and the lower branch H_v of the hyperbolas

$$(x - t\xi)(y - t\eta) = t^2\sigma^2, \quad t = u, v.$$

This is easily seen to hold for the degenerate case $\sigma = 0$, where the hyperbolas are reduced to their asymptotes, and H becomes a square with a diagonal on the first bisectant.

For graphical representation (see Figs. 1 and 2) mark the points (u, u) and (v, v), draw through them the two lines of slope $-f^2/e^2 = -a^2/b^2$, draw the line $y/x = \eta/\xi$ (which varies with θ but lies above the bisectant), and call P and Q the points of intersection of this line with the two preceding ones. The four parallels to the axes through P and Q are the asymptotes of the hyperbolas. The latter are easily seen to intersect (if at all) in M_1 and M_2 on a line parallel to and below the negatively sloped diagonal of the rectangle of diagonal PQ. In case of intersection the region of admissible x and y consists of the two segments between this line and the two hyperbolas. For future use let us draw also the line $y/x = f^2/e^2 = a^2/b^2$ which is always above the bisectant, but may be on either side of $y/x = \eta/\xi$, and also on either side of the left extremity of the region H.

5. CONDITION FOR AN ELLIPSE AT AN ANGLE θ OR $\pi/2 - \theta$

If a' is not required to exceed b', the angle of the major axis of the acceptable ellipse with the major axis of the average one may be either θ or $\pi/2 - \theta$. Such an ellipse exists if the branches H_u and H_v intersect, which is assured if the hyperbolas $n - mu + u^2 = 0$ and $n - mv + v^2 = 0$ intersect inside of the rectangle of diagonal PQ, that is, if, and only if, for the abscissa x of the intersection point, $u\xi \leq x \leq v\xi$, $u\eta \leq y \leq v\eta$.

For the intersection point $M(X, Y)$ we get easily $m = u + v$, $n = uv$, or $\eta X + \xi Y = u + v$, $XY = uv$.

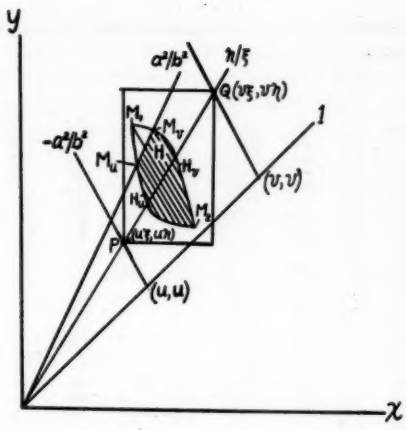

FIG. 1. Small eccentricity. Labels on lines show slopes.

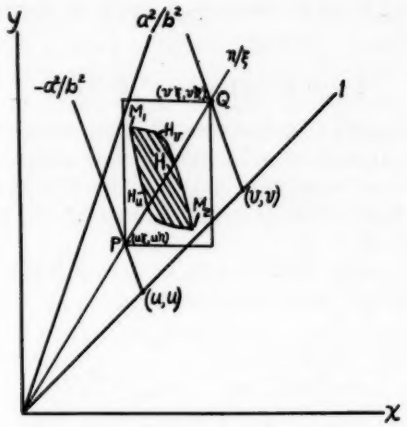

FIG. 2. Large eccentricity. Labels on lines show slopes.

Hence, eliminating Y, and then X,

$$F(X)=\eta X^2-(u+v)X+uv\xi=0, \tag{5}$$

$$G(Y)=\xi Y^2-(u+v)Y+uv\eta=0. \tag{6}$$

For the existence of X and Y the discriminant of these equations must be non-negative: $(u+v)^2-4uv\xi\eta\geq 0$, or, putting $\kappa=((u/v)^{\frac{1}{2}}+(v/u)^{\frac{1}{2}})/2$,

$$\kappa^2\geq 1+\sigma^2. \tag{7}$$

To determine the position of $u\xi$ and $v\xi$ relative to the roots of (5), consider $F(u\xi)=\xi\sigma^2u^2$ and $F(v\xi)=\xi\sigma^2v^2$. Both these quantities being positive, neither $u\xi$ nor $v\xi$ is between the roots. Now, the arithmetic mean of the roots is $(u+v)/2\eta$, and since $u+v\leq 2v$, it certainly is $\leq v/\eta\leq v\xi\eta/\eta$ (since $\xi\eta\geq 1$) $=v\xi$. Thus both roots are $\leq v\xi$. Next, since $v\geq u$, $\kappa\leq(v/u)^{\frac{1}{2}}$. Hence, since $1+\sigma^2\leq\kappa^2$, we have $1+\sigma^2\leq\kappa\kappa\leq\kappa(v/u)^{\frac{1}{2}}$ or $\xi\eta\leq(u+v)/2u$, which proves that both roots are not smaller than $u\xi$. Thus (7) is shown to be the only condition for the intersection of H_u and H_v, and for the existence of H. For $\kappa^2=1+\sigma^2$, H_u and H_v are tangent.

6. CONDITION FOR AN ELLIPSE AT AN ANGLE θ

If the major axis of the other ellipse makes an angle θ with that of the average one, $a'\geq b'$. This implies $a^2x\geq b^2y$ or $y/x\leq f^2/e^2$. In order that at least one such ellipse exist, the right extremity of H must satisfy the last equality because y/x is obviously a minimum there. The x coordinate of this extremity is the larger root of (5), say X_2. We have $X_2Y_2=uv$, and $Y_2/X_2\leq f^2/e^2$. Hence,

$$X_2\geq\frac{e}{f}(uv)^{\frac{1}{2}}. \tag{8}$$

Now

$$F(e(uv)^{\frac{1}{2}}/f)=f^{-2}[(e^2\eta+f^2\xi)uv-(u+v)ef(uv)^{\frac{1}{2}}].$$

Note that $e^2\eta+f^2\xi=e^2+f^2$. Hence

$$F(e(uv)^{\frac{1}{2}}/f)=(2euv/f)\left[\frac{1}{2}\left(\frac{e}{f}+\frac{f}{e}\right)-\frac{1}{2}\left(\left(\frac{u}{v}\right)^{\frac{1}{2}}+\left(\frac{v}{u}\right)^{\frac{1}{2}}\right)\right].$$

For $s\geq 1$, $s+1/s$ is an increasing function of s. Therefore, the expression in the brackets is negative if $f^2/e^2<v/u$, and only then. Since $f/e=a/b$, we can distinguish two cases as follows:

Small Eccentricity: $a^2/b^2\leq v/u$

$F(e(uv)^{\frac{1}{2}}/f)\leq 0$, hence $e(uv)^{\frac{1}{2}}/f$ is between the roots, and inequality (8) is satisfied, if only the roots exist. But this they surely do, since in this case

$$\kappa^2\geq\frac{1}{4}\left(\frac{e}{f}+\frac{f}{e}\right)^2=\frac{1}{4}\left(\frac{e}{f}-\frac{f}{e}\right)^2+1=\frac{e^2f^2}{4}+1\geq 1+\frac{e^2f^2}{4}\sin^2 2\theta=1+e^2f^2\alpha^2\beta^2=1+\sigma^2,$$

and (7) is surely satisfied. *There is no restriction on* θ.

Large Eccentricity: $a^2/b^2 \geq v/u$

$F(e(uv)^{\frac{1}{2}}/f) \geq 0$, and $e(uv)^{\frac{1}{2}}/f$ is not between the roots. It must then be smaller than either root, if (8) is to be satisfied, and thus it must be smaller than their arithmetic mean: $e(uv)^{\frac{1}{2}}/f \leq (u+v)/2\eta$ or $e\eta \leq \kappa f$.

First note that $\theta > \pi/4$, that is, $\beta^2 > \frac{1}{2}$ is impossible. In fact, otherwise,

$$e^2\eta^2 = e^2(1+f^2\beta^2)^2 > e^2(1+f^2/2)^2$$
$$= e^2 + e^2f^2 + e^2f^4/4 = f^2 + e^2f^4/4$$
$$= f^2\left(1+\frac{1}{4}e^2f^2\right) = f^2 - \frac{1}{4}\left(\frac{e}{f}+\frac{f}{e}\right)^2 \geq \kappa^2 f^2,$$

instead of $e\eta \leq \kappa f$. Consequently $\beta^2 \leq \frac{1}{2}$. Then

$$e^2\eta^2 = e^2\eta(1+f^2\beta^2) \leq \eta(e^2+e^2f^2/2)$$
$$= \eta(f^2 - e^2f^2/2) \leq \eta(1-e^2\beta^2)f^2 = f^2\xi\eta = (1+\sigma^2)f^2.$$

But if (7) is satisfied, this entails $e\eta \leq \kappa f$, and both roots are below $e(uv)^{\frac{1}{2}}/f$, by virtue of (7) alone.

Thus (7) and $\beta^2 \leq \frac{1}{2}$ have been shown to be the conditions for an acceptable ellipse at an angle θ. Since $\kappa^2 - 1 = (v-u)^2/4uv$ and $\sigma^2 = e^2f^2 \sin^2 2\theta/4$, this condition can be written

$$\sin 2\theta \leq \frac{v-u}{(uv)^{\frac{1}{2}}} \Big/ ef, \quad \theta \leq \pi/4. \tag{9}$$

This condition holds even for a small eccentricity, since $ef = (f/e - e/f)$ and $(v-u)/(uv)^{\frac{1}{2}} = [(v/u)^{\frac{1}{2}} - (u/v)^{\frac{1}{2}}]$, so that the right-hand side of condition (9) can be less than 1 only when $(v/u)^{\frac{1}{2}} < f/e = a/b$, which corresponds with a large eccentricity. The intermediate case $\theta = \pi/4$ occurs when the most tilted ellipse becomes a circle, $a' = b'$; in fact, in this case $\eta = 1 + f^2/2 = 1 + \frac{1}{2}(f^2/e^2 - 1) = 1 + (v-u)/2u = (u+v)/2u$ and Eq. (5) gives $X = u$, that is, $Y = v$, so that $a^2X = a^2u = b^2v = b^2Y$.

7. THE EXTREME VALUES OF x AND y

For a large eccentricity the whole region H is acceptable, and the extreme values of x are the roots X_1 and X_2 of Eq. (5); the extreme values of y are then uv/X_1 and uv/X_2.

For a small eccentricity only the part of H under the "circle" line $y/x = f^2/e^2$ is acceptable. Its right extremity is (X_2, Y_2), as before, but its left extremities are the intersections of the "circle line" and the branches H_u and H_v, say M_u and M_v. X_u, the abscissa of M_u, is the minimum x; Y_v—the ordinate of M_v—is the maximum y:

$$X_u \leq x \leq X_2; \quad Y_2 \leq y \leq Y_v.$$

Consider now the extreme values of x and y at variable θ. Eq. (5) is easily transformed into

$$(e^2uv - f^2X^2)\beta^2 = (X-u)(X-v).$$

For a large e both $X_{1,2}$ satisfy $fX > e(uv)^{\frac{1}{2}}$; hence $u < X_{1,2} < v$, and, consequently, $u < x < v$, since x is between X_1 and X_2. For a small e only X_2 satisfies $fX > e(uv)^{\frac{1}{2}}$, and thus $X_2 < v$. Consider now the lower limit X_u. As θ increases, the left half of H_u rises, and its intersection with the circle line moves to the right. Thus X_u is seen to increase with θ, its minimum being the value u at $\theta = 0$; $X_u \geq u$, and we have again $u \leq x \leq v$. The same argument holds for Y_v and y.

Since in all cases $u \leq x \leq v$, and these limits are actually attained at $\theta = 0$, the extreme values of x and y, at variable θ, are u and v.

TABLE I.

	Measured in equiluminous plane ($Y=1$)					$p=0.10$		$l=4.32$	
	$1/l$	a	b	$c^2=a^2-b^2$	$.404ab/c^2$	$\theta(°)$	a'/a	θ_{M+S}	p_{M+S}
23	0.160	.203	.0075	.0412	.015	0.43	.984	4.°0	0.62
24	0.185	.128	.005	.0163	.0157	0.45	.984	2.°6	0.46
25	0.193	.108	.005	.0116	.0188	0.54	.984	2.°1	0.34
26	0.359	.0152	.0041	.000214	.118	3.4	.983	6.°7	0.19
27	0.302	.0122	.0054	.000118	.226	6.5	.979	3.°8	0.06
28	0.353	.0144	.0053	.000179	.172	5.0	.981	6.°4	0.13
29	0.285	.0183	.0056	.000303	.137	4.0	.982	2.°9	0.075
30	0.253	.0206	.0062	.000385	.134	3.9	.982	1.°1	0.03
31	0.200	.0227	.0044	.000497	.081	2.34	.984	1.°7	0.07
32	0.283	.0150	.0031	.000215	.087	2.5	.984	2°.7	0.11
33	0.220	.0418	.0055	.001718	.0546	1.57	.984	0.°7	0.04
34	0.177	.0403	.0036	.001607	.0366	1.05	.984	3.°0	0.27
35	0.120	.0166	.0032	.000265	.081	2.33	.984	6.°2	0.25
36	0.223	.0188	.0051	.000327	.120	3.45	.983	0.°5	0.02
37	0.200	.0128	.0051	.000138	.191	5.5	.980	1.°7	0.03
38	0.000	.0111	.0070	.000074	.423	11.8	.973	13.°0	0.11
39	0.000	.0216	.0064	.000424	.132	3.8	.982	13.°0	0.31
40	0.366	.0218	.0102	.000372	.242	7.0	.978	7.°0	0.10
41	−0.025	.0124	.0100	.000054	.928	34.5	.928	14.°4	0.05
42	0.253	.0214	.0036	.000445	.070	2.0	.984	1.°2	0.06
43	0.232	.0269	.0065	.000681	.104	3.0	.983	0.°0	0.00
44	0.250	.0350	.0086	.001151	.106	3.1	.983	1.°0	0.03
45	0.177	.0350	.0034	.001213	.0393	1.13	.984	3.°0	0.25
46	0.236	.072	.0070	.00513	.040	1.14	.984	0.°2	0.02
47	0.258	.079	.0120	.00609	.063	1.8	.984	1.°4	0.08

8. THE MOON-SPENCER HYPOTHESES

In a paper entitled "A metric for colorspace," Parry Moon and Domina E. Spencer[2] advanced

[2] Parry Moon and Domina E. Spencer, "A metric for color space," J. Opt. Soc. Am. **33**, 260–269 (1943).

a few hypotheses concerning the lengths and directions of the MacAdam ellipses transferred to the equiluminous plane $Y=1$. The first of these hypotheses states that the MacAdam ellipses have parallel axes, the common slope of the major axes being 4.32 with respect to the XZ coordinate system in the equiluminous plane.

The formula for the maximum possible angular deviation θ permits us to verify this hypothesis. If it were true, the angle of the major axis of any average ellipse with the direction of slope 4.32 should not exceed the maximum value of θ for this ellipse, this value being given by $\sin 2\theta = 4p/ef(1-p^2)$.

Table I, computed by D. L. MacAdam, lists successively: the number of the figure showing the corresponding average ellipse in reference 1; the reciprocal of the slope of its major axis; the lengths a, b of the semi-axes; the square of the linear eccentricity; the values of $\sin 2\theta$ assuming $p=0.10$, which results in $\sin 2\theta = 0.404ab/c^2$; the corresponding value of θ; the corresponding ratio of the major axes; the value θ_{M+S} of θ implied by the assumption that the true value of the slope is 4.32; the least percentage error p_{M+S} necessary to make the deviation θ_{M+S} acceptable, that is, to make it the maximum possible angular deviation.

If the hypothesis of parallel axes is true, θ_{M+S} should not exceed θ, or—to use another point of view—p_{M+S} should not exceed 0.10. The estimate $p=0.10$ is justified by MacAdam, in a private communication, as follows: "I have assumed $p=0.10$ in order to be safe. Actually, this is the probable error of a single determination of an isolated radius based on fifty observations. Inspection of the figures I published shows that although occasional points depart more than ten percent from the average ellipses, more than half of them agree within ten percent with the collinear radii of the average ellipses. Any ellipse that may be drawn with radii differing more than ten percent from any average ellipse falls inside several successive experimental points and/or outside several other successive points, implying *systematic* errors greater than there is any reason for assuming. These statements apply to the ellipses in the equiluminous plane, as well as to those which I published."

Further: "The excesses of the errors p_{M+S} in the last column over 0.10 represent systematic errors which in the case of eight ellipses are larger than I would agree are possible in my experiments."

The other hypotheses formulated by Moon and Spencer depend for their meaning on the hypothesis just examined. Unless the axes are found to be parallel, it is meaningless to state that ellipses whose minor axes lie on the same line have equal major axes, etc. This makes also pointless the subsequent quantitative hypotheses concerning the alleged common length of these axes.

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Specification of Railroad Signal Colors and Glasses

KASSON S. GIBSON, GERALDINE WALKER HAUPT, AND HARRY J. KEEGAN
National Bureau of Standards, Washington, D. C.

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This paper is a continuation of RP1209 and describes the cooperative work done by the Association of American Railroads Signal Section, Corning Glass Works, and the National Bureau of Standards, leading to the formulation of the AAR Signal Section specifications for signal colors and glasses. The previous paper defined the luminous transmission scale used by the signal engineers and glass manufacturers. The present paper describes the glasses selected by these engineers to define the limits of acceptable chromaticities afforded by these glasses when combined with kerosene or electric illuminant. The spectral transmissions of the glasses are given, together with the luminous transmissions and chromaticities for the specified illuminants. The photometric and colorimetric parts of the AAR Signal Section three-part specifications are illustrated, and the reasons given for the choice of tolerances both on the acceptable signal colors and on the glasses certified by the National Bureau of Standards as duplicates of the standard limit glasses. Various other data of interest are given, including the expression of the permissible chromaticities of signal colors in a uniform-chromaticity-scale coordinate system.

I. INTRODUCTION

THIS is the second of a series of papers describing the work of the National Bureau of Standards on the color standardization of railroad signal glasses. This standardization has resulted from the cooperative efforts of the Signal Section of the Association of American Railroads (formerly the American Railway Association), Corning Glass Works, and the National Bureau of Standards.

The first paper[1] in the series gave a historical résumé of signal-color activities of the AAR Signal Section with particular reference to the specifications issued by that organization (or its precursors) in 1908, 1918, and 1935. Various acknowledgments and references to previous work were also given which are not repeated here.

The principal purpose of the previous paper was to describe the methods and data used in the derivation of the luminous-transmission scale now used by the signal engineers, and to express that scale on a fundamental, absolute basis. The end result of that work is given in Table I, which is a transcription of Table VII of the previous paper.

It may be seen that for each of the six signal colors used by the railroad engineers—designated by them as red, yellow, green, blue, purple, and lunar white—the luminous transmissions of glasses are expressed on an arbitrary scale with symbol T_{AAR}. The expression of that scale (in reality six scales, a different one for each color) on an absolute basis with illuminant at 2360°K is given in Table I.

The purpose of the present paper is to consider the chromaticities of railroad signal colors and glasses. The parts of the 1908 and 1918 specifications dealing with chromaticity are noted, the glasses newly selected by the signal engineers (beginning in 1931) to define the limits of permissible colors are listed and their spectral and luminous transmissions given, the methods used to express the results in colorimetric terms suitable for specification purposes are described, and pertinent parts of the current railroad signal specifications are quoted and illustrated.

TABLE I. Relation between values of T_{AAR} and of T_{2360} which defines the luminous transmission scale used in the present AAR signal-glass specifications.

Color designation of glass	AAR transmission, T_{AAR}	Equivalent luminous transmission, 1931 ICI standard observer, illuminant 2360°K, T_{2360}	Color designation of glass	AAR transmission, T_{AAR}	Equivalent luminous transmission, 1931 ICI standard observer, illuminant 2360°K, T_{2360}
Red	100.0	0.069	Blue	100.0	0.0223
Yellow	100.0	.247	Purple	100.0	.0129
Green	100.0	.119	Lunar white	100.0	.190

[1] Kasson S. Gibson and Geraldine Walker Haupt, "Standardization of the Luminous-Transmission Scale Used in the Specification of Railroad Signal Glasses," J. Research Nat. Bur. Stand. **22**, 627 (1939) RP 1209, and J. Opt. Soc. Am. **29**, 188 (1939).

The work covered in these two papers, and many other details of the investigation, may be found in seven formal reports which were issued to the cooperating agencies over the period from 1932 to 1938.[2]

II. METHODS USED TO SPECIFY THE CHROMATICITIES OF RAILROAD SIGNAL COLORS AND GLASSES

Workers in colorimetry have become so familiar with the methods of computation and specification in terms of the 1931 ICI Standard Observer and Coordinate System for Colorimetry that discussion and explanations are often no longer needed. This has only recently been true, however, and at the times of issue of the 1908 and 1918 railroad signal glass specifications[3] little knowledge and no convenient computational procedures were available for such work. Furthermore the art of spectrophotometry had not progressed sufficiently, at least in 1908, to warrant the precise colorimetric standardization which has become commonplace in recent years.

It was noted in the previous paper that a chromaticity (mixture) diagram, so essential in specifying the chromatic properties of signal lights, had been illustrated in colors and used by Dr. Churchill in 1905 in his study of the characteristics of signal glassware.[4] No attempt was made, however, in either the 1908 or 1918 specifications to use a method of specification based on such a system. Instead we find the following qualitative restrictions expressed in terms of spectral hues.

Excerpts from 1908 Railway Signal Association Specifications for Signal Roundels and Lenses.

"*Red.*—Will be of such quality that all yellow rays of light are absorbed, the spectrum being either red or red and orange. The photometric value shall be: light 125, standard 100, dark 75.

"*Green.*—Will be of the color known as admiralty green, having a slightly bluish tint. The spectrum shall show very little yellow, being a full green with some blue. The photometric value shall be: light 125, standard 100, dark 75.

"*Yellow.*—Will give a spectrum showing a full yellow band, most of the red and slightly of the green. The photometric value shall be: light 120, standard 100, dark 80.

"*Blue.*—Will give a spectrum having a full blue band, with a narrow band of green. The photometric value shall be: light 125, standard 100, dark 75.

"*Purple.*—Will give a spectrum showing a considerable proportion of both red and blue. The photometric value shall be: light 125, standard 100, dark 75.

"*Lunar White.*—Shall show a maximum of absorption for the yellow. The photometric value shall be: light 120, standard 100, dark 80."

The scales on which the photometric values of the 1908 and 1918 specification are based are roughly as defined in Table I. This is discussed in the previous paper.

Excerpts from 1918 Railway Signal Association Specification 6918 for Signal Roundels, Lenses and Glass Slides.

[2] Standardization of railway signal glasses—Reports on measurements and investigations undertaken by the Colorimetry Section of the National Bureau of Standards at the request of the Signal Section, American Railway Association.

Reports 1 to 5, published in Signal Section Proc., Am. Railway Assoc. **30**, 384 (1933):

Report 1. K. S. Gibson. The transmission (A.R.A. scale) of 36 specimens of signal glass relative to transmission of 6 A.R.A. standards marked "J. C. Mock 10–3–30," a report on measurements made at Corning Glass Works, December 9–11, 1930 (June 1, 1932).

Report 2. K. S. Gibson and Geraldine K. Walker. Measurements of spectral and luminous transmissions leading to the derivation of new A.R.A. transmissions for the 36 glasses listed in report 1 (October 24, 1932).

Report 3. Geraldine K. Walker and K. S. Gibson. Spectral and luminous transmissions and derivation of new values of A.R.A. transmission for the 22 "limit" glasses selected by committee VI, A.R.A., at Corning, November 5–6, 1931, and engraved "J.C.M. 11–6–31" (December 2, 1932).

Report 4. K. S. Gibson and Geraldine K. Walker. Chromaticities and luminous transmissions, with illuminants at 1900°K and 2848°K, for the 22 "limit" glasses described in Report 3 (January 30, 1933).

Report 5. K. S. Gibson. Tentative specifications for railway signal colors (April 27, 1933).

Reports 6 and 7. K. S. Gibson, Geraldine Walker Haupt, and H. J. Keegan, published in Signal Section Proc. Assoc. Am. Railroads **36**, 136 (1939):

Report 6. Examination of 65 duplicate limit glasses (July 26, 1934).

Report 7. Colorimetric data leading to specification 59-38 for kerosene hand lantern globes; comparison of specifications 59-38, 69-38, and 69-35; certification of duplicate lantern glasses (September 28, 1938).

[3] Specifications for Signal Roundels, Lenses, and Glass Slides. Proc. Railway Signal Assoc. **5** (1908). Railway Signal Association Specification 6918, Signal Roundels, Lenses, and Glass Slides (1918).

[4] Wm. Churchill, "The Roundel Problem," a paper presented at the Ninth Annual Meeting of the Railway Signal Association, Niagara Falls, New York, October 10–12, 1905.

"*Red.*—Shall be of such quality that all yellow rays of light emitted by the sodium flame are absorbed, the spectrum being either red, or red and orange.

"*Green.*—Shall be of the color known as admiralty green, having a slightly bluish tint as seen in daylight. The spectrum shall show most of the blue and green, a slight amount of yellow and not more than a trace of orange and red.

"*Yellow.*—Shall give a spectrum showing most of the red, all of the yellow, and part of the green, but no blue.

"*Blue.*—Shall give a spectrum showing most of the blue, some green, and almost no red.

"*Purple.*—Shall give a spectrum showing most of the blue, some green, and a narrow band of the extreme red.

"*Lunar White.*—Shall show blue and green, with about ten (10) percent of yellow and orange, and some red. It shall appear a light blue when viewed by daylight, and when placed in front of a yellow kerosene flame, it shall make this flame appear white."

In addition, in the 1918 specification there is given a table showing the light and dark limits for each of the six colors: red 160 to 100, green 175 to 125, yellow 140 to 100, blue 125 to 75, purple 125 to 75, and lunar white 120 to 80.

While it is obvious, therefore, that chromaticity limits were not given as such in either specification, the light and dark limits were apparently tacitly used as chromaticity limits. This, combined with the spectral restrictions noted above, served with considerable effectiveness to protect American railroads against signal glassware outside the chosen chromaticity and transmission ranges. It was noted in the previous paper that the 1908 specification appears to have been the first effort in this country to place the colorimetric part of a purchase specification on a fundamental basis, the specification being based on spectrophotometric data and establishing tolerances within which the manufactured product must come.

During the 1920's great advances were made in colorimetry. In 1922 the Optical Society of America Colorimetry Committee published a report[5] giving data and computational procedures for deriving and specifying the chromaticity of a color based on spectrophotometric data. In 1924 standard luminosity factors[6] were adopted by the International Commission on Illumination in terms of which the intensities of colored lights and the luminous transmissions of signal glasses may be expressed. In 1931 the International Commission on Illumination adopted data defining a standard observer and coordinate system for colorimetry[7] which has become the recognized method for specifying color. It incorporates the standard luminosity factors. The computational procedure, operating on spectrophotometric data, results in coordinates serving to specify the chromaticity of a color. In this coordinate system, x, y, and z represent fractional parts of hypothetical reddish, greenish, and bluish primaries ($x+y+z=1$) and it is customary to express the chromaticity diagram in terms of x and y. This system is now well known and widely used and the reader is referred to the other publications listed for further information.

Along with this advance in colorimetry there occurred further progress in the manufacture of signal glassware. The status of this work was summarized by Dr. H. P. Gage in 1928.[8]

In 1930 was initiated the program in which the AAR Signal Section, Corning Glass Works, and the National Bureau of Standards have cooperated, as described in the previous paper. In 1931 the railroad signal engineers selected a completely new set of standard glasses explicitly defining new limits of chromaticity for the respective colors. As a result of the work thus started, new AAR Signal Section specifications have appeared over the years from 1935 to 1940.[9]

[5] Optical Society of America Committee on Colorimetry, L. T. Troland, Chairman, "Report for 1920–21," J. Opt. Soc. Am. and Rev. Sci. Inst. **6**, 527 (1922).

[6] Proceedings Sixth Meeting, ICI, Geneva, p. 67 (1924). For résumé of recent work and present status of these ICI luminosity factors, see K. S. Gibson, "Spectral Luminosity Factors," J. Opt. Soc. Am. **30**, 51 (1940).

[7] Proceedings Eighth Meeting, ICI, Cambridge, p. 19 (1931). D. B. Judd, "The 1931 ICI Standard Observer and Coordinate System for Colorimetry," J. Opt. Soc. Am. **23**, 359 (1933). A. C. Hardy, *Handbook of Colorimetry* (The Technology Press, Cambridge, Massachusetts, 1936). "Quantitative Data and Methods for Colorimetry," Chapter VII of the forthcoming OSA Colorimetry Committee report, J. Opt. Soc. Am. **34**, 633 (1944).

[8] H. P. Gage, "Practical Considerations in the Selection of Standards for Signal Glass in the United States," Proc., Intern. Cong. Illum., Saranac Inn, New York, p. 834 (1928).

[9] Specification 69 is entitled Signal Glasses (exclusive of kerosene hand lantern globes). It was published in essentially its present form in 1935, and was designated as 69-35. Slightly revised editions were published in 1938,

TABLE II. Description of glasses selected by AAR Signal Section Committee VI as defining the chromaticity limits of railroad signal colors.

Color designation	Type	Photometric designation	Number of glass	Values of T_{AAR}	Chromaticity limit	Designed for illuminant	Remarks
			AAR Signal Section Specification 69-40				
Red	Except highway crossing	Light	154	177.0	Pale and yellow[a]	Electric, E and Kerosene, K	For pressed ware and disks, heat resisting HR
		Dark	86	102.9			
Red	Highway crossing	Light	75	288.2	Pale and yellow[a]	E	For pressed ware, HR
		Dark	400	217.6			
Yellow	Non-HR	Light	141	214.1	Pale and green	E and K	For pressed ware
		Dark	142	160.8	Red		
Yellow	Disk	[e]	199	270.5	Pale and green	E	For disks, HR
		[e]	200	251.0	Red		
Green	Non-HR	Light	134	205.9	Pale and yellow	E and K	For pressed ware
		Dark	87	150.5	Blue		
Green	Disk	Light	139	193.4	Pale and yellow[b]	E	For disks, HR
		Dark	140	138.7			
Blue	Non-HR	Light	47	130.2	Pale and green	E and K	For pressed ware
		Dark	57	74.7	Red		
Purple	Kerosene	Light	56	131.2	Pale and green[c]	K	For pressed ware, Non-HR
		Dark	47	73.3	Red[c]		
Purple	Electric	Light	80	40.1	Pale and green[c]	E	For disks, HR
		Dark	108	30.3	Red[c]		
Lunar white	Kerosene	Light	45	121.7	Yellow[d]	K	For pressed ware, Non-HR
		Dark	74	79.6	Blue[d]		
Lunar white	Electric	Light	124	205.3	Yellow[d]	E	For disks, Non-HR
		Dark	73	146.6	Blue[d]		
			AAR Signal Section Specification 59-39				
Red	Kerosene lantern	Light	201	256.7	Pale and yellow[a]	K	For hand lantern globes, HR
		Dark	211	145.5			
Yellow	Kerosene lantern	Light	261	297.4	Pale and green	K	For hand lantern globes, HR
		Dark	271	241.2	Red		
Green	Kerosene lantern	Light	137	184.9	Pale and yellow	K	For hand lantern globes, HR
		Dark	322	126.6	Blue		
Blue	Kerosene lantern	Light	141	124.8	Pale and green	K	For hand lantern globes, HR
		Dark	131	56.0	Red		

[a] No chromaticity limit is needed. The dark limit glass is useful, however, in the photometry of red signal glassware.
[b] Non-HR green No. 87 has been accepted as the blue limit for disk greens.
[c] These chromaticity limits have little significance. The purple glass gives a dichromatic signal, and the ratio of red to blue (or total) light is the important criterion.
[d] Green and purple limit glasses were not selected.
[e] In use, one side of each disk is "depolished;" no other restrictions are placed on the luminous transmissions.

The colorimetric parts of these specifications are expressed entirely in the fundamental terms of the 1931 ICI standard observer and coordinate system. Here, as before, the signal engineers have been pioneers in the use of color specifications. It is believed that the suggested "Specification for Railway Signal Colors," appearing in the 1933 Signal Section Proceedings and including a chromaticity (x, y) diagram (similar to Fig. 8, below) on which are plotted points representing the standard glasses and areas

1939, and 1940, 69-40 being the current specification. Similarly specification 59 for kerosene hand lantern globes was published in essentially its present form in 1938, the current edition being designated as 59–39. Copies of these specifications are obtainable from Mr. R. H. C. Balliet, Secretary, AAR Signal Section, 30 Vesey Street, New York, New York.

TABLE III. Spectral transmissions, T_λ, of glasses selected by AAR Signal Section Committee VI as defining the chromaticity limits of railroad signal colors.

Wavelength in millimicrons	Red						Yellow						Green					
	Pressed ware and disk		Highway crossing		Hand lantern globes		Pressed ware		Disk		Hand lantern globes		Pressed ware		Disk		Hand lantern globes	
	L 154	D 86	L 75	D 400	L 201	D 211	L 141	D 142	— 199	— 200	L 261	D 271	L 134	D 87	L 139	D 140	L 137	D 322
380							0.008	0.0002		0.0008			0.121	0.073	0.097	0.040	0.230	0.13
90							.008	.0002		.0009			.242	.152	.150	.082	.294	.19
400							.0075	.0002		.0010			.335	.237	.207	.126	.356	.247
10							.0074	.0002		.0014			.405	.307	.266	.174	.408	.304
20							.0076	.0003		.0020			.465	.366	.315	.222	.457	.362
30							.0087	.0004		.0028			.521	.425	.371	.273	.505	.416
40							.0113	.0007		.0039			.565	.480	.414	.326	.545	.465
450							.0169	.0014		.0054			.617	.541	.459	.373	.582	.512
60							.0271	.0030		.0075			.659	.588	.503	.423	.620	.552
70							.0423	.0064		.0101			.686	.625	.540	.459	.645	.581
80							.0636	.0126		.0137			.696	.638	.565	.483	.662	.600
90							.0952	.0238		.0190			.695	.633	.577	.501	.666	.600
500							.1324	.0424	0.0000	.0289	0.000		.680	.618	.578	.501	.658	.580
10							.186	.0712	.0001	.0526	.001		.656	.584	.569	.483	.628	.540
20							.241	.1102	.0003	.0826	.120	0.000	.610	.526	.536	.450	.578	.481
30							.303	.158	.0126	.1125	.518	.001	.540	.450	.493	.396	.509	.404
40							.367	.214	.289	.157	.705	.048	.462	.366	.430	.333	.434	.319
550							.430	.277	.654	.277	.767	.433	.382	.279	.358	.266	.347	.234
60							.492	.339	.784	.544	.796	.670	.301	.205	.292	.201	.265	.164
70		0.0000					.542	.399	.826	.770	.818	.738	.230	.1424	.224	.1442	.196	.105
80		.0001	0.0000		0.000		.589	.451	.844	.848	.835	.774	.171	.0952	.172	.0996	.1390	.064
90	0.0000	.0002	.037	0.0000	.001		.625	.495	.857	.873	.848	.803	.1211	.0609	.1240	.0660	.0968	.0372
600	.0003	.0005	.27	.010	.051	0.000	.654	.532	.864	.882	.859	.824	.0856	.0375	.0902	.0428	.0653	.0217
10	.037	.0019	.54	.16	.41	.004	.676	.559	.869	.887	.866	.840	.0588	.0225	.0642	.0276	.0437	.0124
20	.41	.022	.685	.60	.715	.22	.693	.579	.874	.890	.870	.854	.0402	.0134	.0460	.0173	.0289	.0072
30	.71	.23	.742	.796	.805	.60	.705	.593	.879	.892	.873	.863	.0270	.0084	.0322	.0109	.0190	.0041
40	.796	.65	.771	.848	.835	.734	.713	.599	.883	.893	.875	.871	.0182	.0051	.0230	.0070	.0127	.0024
650	.820	.798	.790	.866	.846	.784	.718	.602	.887	.894	.876	.877	.0124	.0031	.0167	.0046	.0088	.0015
60	.833	.833	.804	.873	.853	.803	.721	.603	.889	.894	.877	.880	.0088	.0019	.0122	.0031	.0062	.001
70	.842	.844	.817	.879	.858	.813	.723	.601	.890	.894	.877	.883	.006	.001	.0093	.0021	.0045	.000
80	.848	.852	.826	.881	.860	.820	.723	.596	.891	.894	.876	.884	.004	.000	.0070	.0014	.003	
90	.851	.856	.834	.882	.861	.825	.722	.588	.891	.893	.875	.885	.003		.0054	.001	.0025	
700	.853	.858	.841	.883	.862	.826	.720	.580	.891	.892	.873	.884	.002		.0042	.000	.002	
10	.852	.859	.846	.884	.860	.826	.717	.570	.891	.890	.871	.882	.0015		.0033		.0015	
20	.850	.858	.851	.883	.857	.824	.712	.560	.890	.888	.868	.880	.001		.0026		.001	
30	.848	.857	.854	.881	.855	.821	.706	.548	.889	.886	.865	.879	.000		.0021		.000	
40	.846	.855	.857	.879	.852	.818	.700	.535	.888	.884	.862	.877			.0017			
750	.843	.852	.857	.877	.848	.814	.692	.522	.886	.883	.859	.875			.0014			
60	.840	.849	.857	.875	.844	.809	.683	.507	.884	.882	.856	.873			.0011			
70	.836	.846	.857	.873	.841	.805	.673	.492	.882	.881	.853	.871			.0008			
T_{AAR} =	177.0	102.9	288.2	217.6	256.7	145.5	214.1	160.8	270.5	251.0	297.4	241.2	205.9	150.5	193.4	138.7	184.9	126.6

TABLE III.—*Continued.*

Wave-length in milli-microns	Blue				Purple				Lunar white			
	Pressed ware		Hand lantern globes		Kerosene		Electric		Kerosene		Electric	
	L 47	D 57	L 141	D 131	L 56	D 47	L 80	D 108	L 45	D 74	L 124	D 73
380	0.579	0.442	0.50	0.45	0.835	0.783	0.886	0.875	0.828	0.835	0.825	0.819
90	.716	.596	.63	.58	.853	.849	.867	.858	.856	.854	.875	.890
400	.770	.675	.710	.655	.857	.852	.838	.827	.873	.867	.888	.900
10	.790	.718	.738	.685	.831	.823	.787	.780	.867	.858	.884	.888
20	.785	.731	.742	.691	.798	.779	.727	.714	.847	.830	.876	.869
30	.771	.726	.734	.680	.763	.733	.647	.625	.838	.820	.871	.860
40	.751	.707	.717	.659	.727	.684	.558	.527	.830	.807	.866	.851
450	.719	.673	.693	.630	.676	.625	.448	.422	.818	.792	.862	.842
60	.670	.625	.652	.576	.615	.552	.328	.302	.800	.769	.851	.826
70	.590	.530	.564	.470	.504	.426	.197	.172	.764	.718	.824	.792
80	.467	.393	.426	.320	.355	.269	.098	.077	.698	.637	.783	.733
90	.331	.258	.286	.186	.214	.1397	.0408	.0304	.612	.535	.732	.656
500	.225	.165	.197	.112	.1305	.0713	.0189	.0130	.542	.446	.672	.583
10	.1362	.0854	.117	.0529	.0636	.0275	.0076	.0045	.450	.350	.598	.495
20	.0710	.0376	.0601	.0215	.0266	.0087	.0032	.0017	.357	.258	.520	.408
30	.0319	.0135	.0270	.0075	.0088	.0022	.0016	.0007	.266	.174	.434	.319
40	.0191	.0072	.0188	.0044	.0050	.0010	.0017	.0008	.230	.143	.397	.281
550	.0219	.0084	.0244	.0067	.0073	.0017	.0039	.0019	.255	.164	.423	.307
60	.0325	.0123	.0361	.0109	.0147	.0042	.0056	.0029	.306	.211	.470	.357
70	.0254	.0083	.0280	.0071	.0119	.0031	.0023	.0011	.291	.195	.462	.342
80	.0092	.0022	.0096	.0016	.0033	.0006	.0004	.0002	.203	.1231	.373	.253
90	.0024	.0004	.0026	.0003	.0006	.0001	.0001	.0000	.132	.0675	.282	.173
600	.0020	.0003	.0021	.0002	.0005	.0001	.0001	.0000	.128	.0651	.277	.170
10	.0022	.0003	.0021	.0002	.0007	.0001	.0001	.0001	.141	.0743	.293	.185
20	.0019	.0002	.0023	.0003	.0008	.0001	.0001	.0001	.145	.0778	.299	.190
30	.0015	.0002	.0021	.0002	.0007	.0001	.0001	.0001	.138	.0740	.292	.183
40	.0010	.0001	.0016	.0001	.0005	.0001	.0001	.0000	.128	.0654	.276	.168
650	.0010	.0001	.0015	.0001	.0006	.0001	.0001	.0000	.131	.0688	.283	.174
60	.0015	.0002	.0020	.0002	.0018	.0003	.0002	.0001	.165	.0942	.327	.214
70	.0035	.0003	.0054	.0006	.0075	.0015	.0012	.0004	.248	.161	.425	.302
80	.0109	.0005	.017	.0032	.043	.016	.0080	.0045	.398	.303	.560	.453
90	.0275	.0020	.042	.014	.19	.11	.045	.036	.587	.514	.707	.628
700	.042	.0030	.071	.027	.44	.35	.18	.16	.734	.700	.810	.766
10	.050	.0040	.090	.037	.68	.61	.41	.38	.821	.812	.865	.846
20	.051	.0041	.096	.041	.80	.77	.62	.60	.854	.862	.888	.880
30	.049	.0037	.096	.040	.859	.84	.76	.75	.872	.884	.900	.892
40	.047	.0034	.093	.039	.882	.874	.84	.83	.877	.893	.902	.897
750	.045	.0031	.090	.037	.892	.885	.878	.875	.878	.895	.903	.899
60	.043	.0026	.087	.035	.895	.889	.897	.895	.878	.895	.904	.900
70	.041	.0021	.084	.033	.896	.890	.902	.902	.878	.895	.904	.900
T_{AAR} =	130.2	74.7	124.8	56.0	131.2	73.3	40.1	30.3	121.7	79.6	205.3	146.6

TABLE IV. Luminous transmissions, T_w, ratios of red to total luminous transmission, T_r/T_w, and chromaticity coordinates, x, y, z, for glasses selected by AAR Signal Section Committee VI as defining the chromaticity limits of railroad signal colors.

Color designation	Number of glass	Illuminant at 1900°K				Illuminant at 2360°K						Illuminant at 2848°K			
		x	y	z	T_w	x	y	z	T_w	T_{AAR}	T_r/T_w	x	y	z	T_w
Red	154	0.7148	0.2852	0.0000	0.1564	0.7138	0.2862	0.0000	0.1222	177.0	—	0.7132	0.2867	0.0000	0.1009
	86	.7234	.2766	.0000	.0944	.7228	.2772	.0000	.0711	102.9	—	.7224	.2776	.0000	.0572
	75	.6967	.3032	.0001	.2431	.6944	.3055	.0001	.1989	288.2	—	.6927	.3072	.0001	.1698
	400	.7108	.2891	.0001	.1898	.7096	.2904	.0001	.1502	217.6	—	.7088	.2912	.0001	.1251
	201	.7051	.2948	.0001	.2205	.7036	.2963	.0001	.1771	256.7	—	.7025	.2974	.0001	.1493
	211	.7178	.2822	.0000	.1300	.7171	.2829	.0000	.1004	145.5	—	.7165	.2835	.0000	.0823
Yellow	141	.5963	.3976	.0062	.5571	.5740	.4157	.0103	.5296	214.1	—	.5560	.4291	.0149	.5082
	142	.6113	.3861	.0027	.4262	.5934	.4026	.0041	.3978	160.8	—	.5794	.4151	.0056	.3762
	199	.6036	.3955	.0009	.7137	.5878	.4111	.0011	.6692	270.5	—	.5762	.4226	.0012	.6334
	200	.6147	.3836	.0018	.6708	.6000	.3972	.0027	.6210	251.0	—	.5889	.4073	.0038	.5823
	261	.5873	.4107	.0020	.7669	.5669	.4306	.0026	.7358	297.4	—	.5515	.4454	.0030	.7095
	271	.6151	.3843	.0007	.6456	.6014	.3979	.0008	.5967	241.2	—	.5913	.4078	.0009	.5584
Green	134	.3197	.4944	.1859	.2106	.2749	.4550	.2702	.2442	205.9	—	.2448	.4145	.3407	.2698
	87	.2684	.4976	.2340	.1492	.2316	.4472	.3212	.1784	150.5	—	.2084	.4016	.3899	.2013
	139	.3407	.5025	.1568	.2002	.2951	.4721	.2328	.2294	193.4	—	.2634	.4376	.2990	.2515
	140	.2949	.5138	.1913	.1397	.2555	.4742	.2702	.1645	138.7	—	.2295	.4348	.3357	.1835
	137	.3025	.4974	.2001	.1872	.2602	.4542	.2856	.2193	184.9	—	.2324	.4116	.3561	.2440
	322	.2415	.4942	.2643	.1236	.2099	.4376	.3525	.1502	126.6	—	.1909	.3891	.4200	.1712
Blue	47	.1783	.2049	.6168	.02216	.1595	.1521	.6884	.02909	130.2	0.0089	.1530	.1221	.7249	.03556
	57	.1458	.1387	.7154	.01164	.1436	.1051	.7514	.01669	74.7	.0011	.1440	.0862	.7698	.02155
	141	.1916	.2070	.6014	.02173	.1665	.1522	.6812	.02789	124.8	.0147	.1575	.1212	.7213	.03372
	131	.1543	.1187	.7270	.00876	.1482	.0889	.7630	.01252	56.0	.0088	.1474	.0728	.7798	.01626
Purple	56	.2280	.1475	.6245	.01386	.1765	.1035	.7200	.01692	131.2	.116	.1610	.0818	.7572	.02062
	47	.2158	.1000	.6842	.00752	.1700	.0690	.7610	.00945	73.3	.158	.1579	.0552	.7869	.01200
	80	.2292	.0904	.6804	.00443	.1799	.0564	.7636	.00517	40.1	.188	.1661	.0426	.7913	.00634
	108	.2277	.0758	.6965	.00336	.1786	.0463	.7750	.00390	30.3	.227	.1658	.0352	.7990	.00485
Lunar white	45	.4395	.3981	.1624	.2173	.3651	.3664	.2685	.2306	121.7	—	.3122	.3279	.3599	.2421
	74	.4005	.3766	.2229	.1394	.3216	.3308	.3476	.1509	79.6	—	.2711	.2852	.4437	.1612
	124	.4822	.4106	.1072	.3755	.4169	.3953	.1878	.3891	205.3	—	.3654	.3688	.2658	.4004
	73	.4556	.4032	.1413	.2643	.3840	.3772	.2388	.2779	146.6	—	.3308	.3426	.3266	.2895

representing permissible chromaticities for the six signal colors, is the first published use of the ICI colorimetric system for specification purposes.[10] Methods similar to this have since been followed in specifying the colors and glasses used in traffic, marine, and aviation signaling both here and abroad.[11]

III. STANDARD GLASSES DEFINING LIMITS OF ACCEPTABLE CHROMATICITIES FOR RAILROAD SIGNAL COLORS

At a meeting held at Corning Glass Works on November 5 and 6, 1931, numerous glasses were selected to define the new limits of acceptable chromaticities which it was desired to standardize. These glasses were selected by members of Committee VI of the AAR Signal Section, Mr. J. C. Mock, Chairman. During the course of the work a few of the glasses were superseded by others. As a group they comprise the standards covering the use of roundels, lenses, slides (pressed ware), and disks for railroad signaling, and are designed for use with "electric" (incandescent) and/or "kerosene" illuminants. They include the colors designated as red, yellow, green, blue, purple, and lunar white.

At a meeting of Subcommittee C of Committee VI, Mr. A. S. Haigh, Chairman, held at Corning Glass Works in June, 1935, additional glasses were selected representing the chromaticity limits for red, yellow, green, and blue kerosene hand lantern globes, and in 1939 the limits for highway-crossing red were likewise selected.

It may be noted that all of these standard limit glasses were selected by experienced signal

[10] K. S. Gibson, Report No. 5, Tentative Specifications for Railway Signal Colors, Signal Section Proc., Am. Railway Assoc. **30**, 429 (1933).

[11] See, for example, (1) Standards of the Institute of Traffic Engineers, Technical Report No. 1, Adjustable face traffic control signal head standards, 1940 Proceedings, (2) Bureau of Marine Inspection and Navigation (now part of U. S. Coast Guard), Proposed Specification covering navigation lights for vessels, alteration D (1941), (3) Army-Navy Aeronautical Specification: Colors; aeronautical lights and lighting equipment; AN-C-56 (1942); (4) Proceedings ICI, Tenth Session, Scheveningen, Holland (1939), condensed unofficial version edited and published by the United States National Committee, Figure 17.

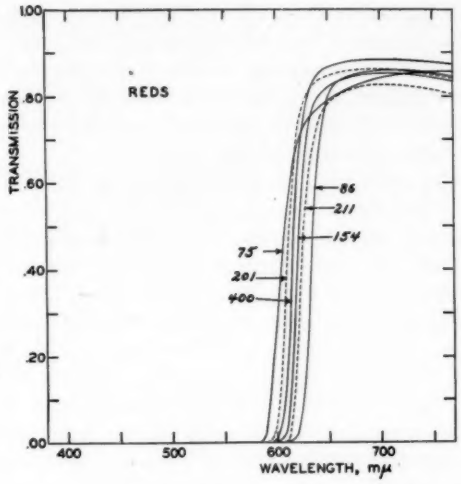

FIG. 1. Spectral transmissions of standard limit glasses designated as red. Nos. 154 and 86, pressed ware and disk; 75 and 400, highway crossing; 201 and 211, lantern. See Tables II and III for further identification.

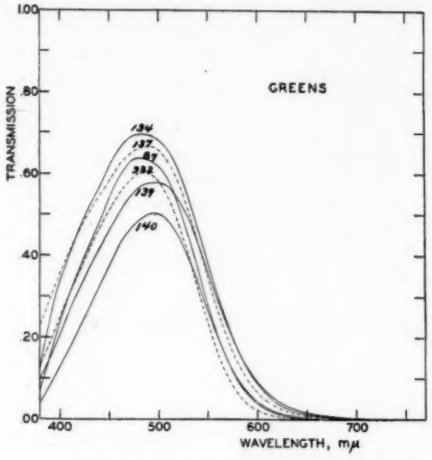

FIG. 3. Spectral transmissions of standard limit glasses designated as green. Nos. 134 and 87, pressed ware (non-HR); 139 and 140, disk; 137 and 322, lantern. See Tables II and III for further identification.

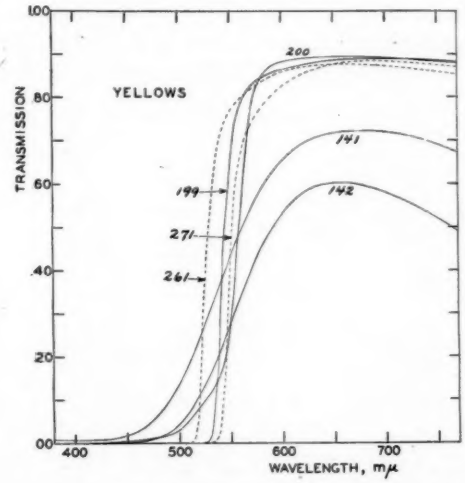

FIG. 2. Spectral transmissions of standard limit glasses designated as yellow. Nos. 141 and 142, pressed ware (non-HR); 199 and 200, disk; 261 and 271, lantern. See Tables II and III for further identification.

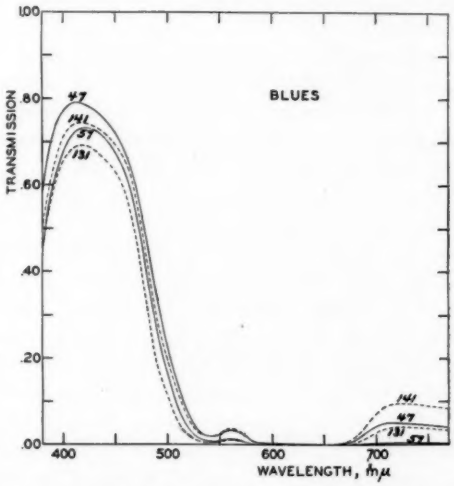

FIG. 4. Spectral transmissions of standard limit glasses designated as blue. Nos. 47 and 57, pressed ware; 141 and 131, lantern. See Tables II and III for further identification.

engineers as a result of field tests conducted at Corning Glass Works. Final selection was based both on the desired differentiation of signals of the various colors and on reasonable manufacturing tolerances required for each of the colors. Numerous details may be found in the seven published reports from the National Bureau of Standards[2] and in the Proceedings of the AAR Signal Section, to which reference is made in the previous paper. These standard limit glasses have all been deposited with the National Bureau of Standards.

A description of the glasses finally selected as

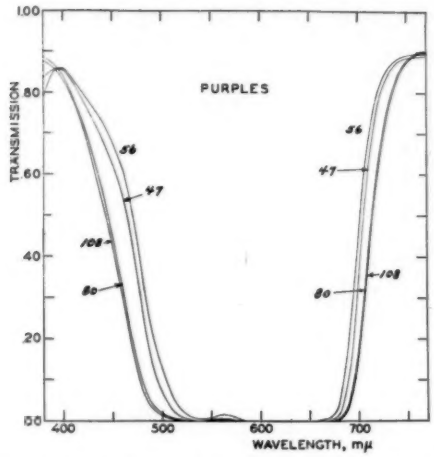

FIG. 5. Spectral transmissions of standard limit glasses designated as purple. Nos. 56 and 47, kerosene; 80 and 108, electric. See Tables II and III for further identification.

standards (and in current use) is given in Table II.[12]

Their spectral transmissions are given in Table III. In Table IV are given (1) the chromaticity coordinates and luminous transmissions of each glass in combination with the illuminants of color temperature 1900°K, 2360°K, and 2848°K, (2) the T_{AAR} value for each glass, and (3) the ratio of red to total luminous transmission, T_r/T_w, for the blue and purple glasses for 2360°K. The values given in Table IV are all uncertain in the last figure given; this uncertainty relates to uncertainties in the spectral transmissions of Table III and to rejection errors or other factors in the methods of computation. In some cases this uncertainty may extend slightly into the next to last figure. Values of T_{AAR} are derived from values of T_{2360} by conversion factors carried to one more significant figure than are given in Table I.

The spectral transmissions given in Table III are illustrated in Figs. 1 to 6. The values of x and y given in Table IV are plotted in the charts illustrating the final specifications, Figs. 7 and 8, below. Various data on certain of the superseded limit glasses are given in the several National Bureau of Standards published reports to which reference has already been made.

The spectral transmissions given in Table III were determined mostly on the König-Martens visual spectrophotometer[13] and the Gibson photoelectric spectrophotometer.[14] Measurements were made usually at every 10 mμ from 380 to 770 mμ, the photoelectric measurements extending usually from 380 to 500 mμ and from 660 to 770 mμ, and the visual measurements from somewhere in the range 450 to 500 mμ to somewhere in the range 680 to 720 mμ, in addition to the mercury wave-lengths 404.7 and 435.8 mμ. The values adopted and given in Table III are usually uncertain in the last figure given. All of the curves shown in Figs. 1 to 6 are typical with one exception. This exception is the curve for red-limit disk yellow 200, Fig. 2. Glasses 199 and 200 are of the type known as "selenium yellows," characterized usually by the high transmission in the red, orange, and yellow, essentially com-

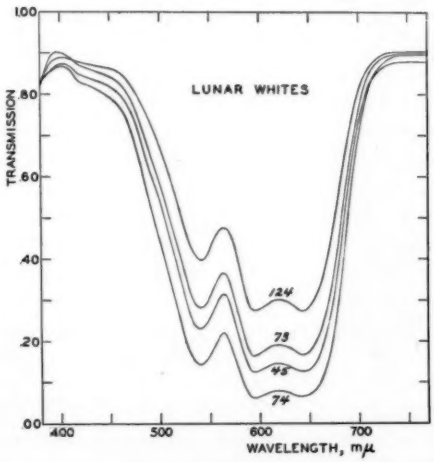

FIG. 6. Spectral transmissions of standard limit glasses designated as lunar white. Nos. 45 and 74, kerosene; 124 and 73, electric. See Tables II and III for further identification.

[12] In describing these glasses the expressions "light limit" and "dark limit" have been retained because of their widespread use among signal engineers and glass manufacturers. The term, dark limit, is more or less appropriate but the term, light limit, is inappropriate since there is no upper limit of luminous transmission placed on any glassware in the specifications. The "light limit" glasses all define chromaticity limits, as indicated in Table II. Likewise, the values of T_{AAR} are given in the table because of their widespread usage in describing signal glasses.

[13] H. J. McNicholas, "Equipment for Routine Spectral Transmission and Reflection Measurements," Bur. Stand. J. Research **1**, 793 (1928), RP 30.

[14] K. S. Gibson, "Direct-Reading Photoelectric Measurement of Spectral Transmission," J. Opt. Soc. Am. and Rev. Sci. Inst. **7**, 693 (1923).

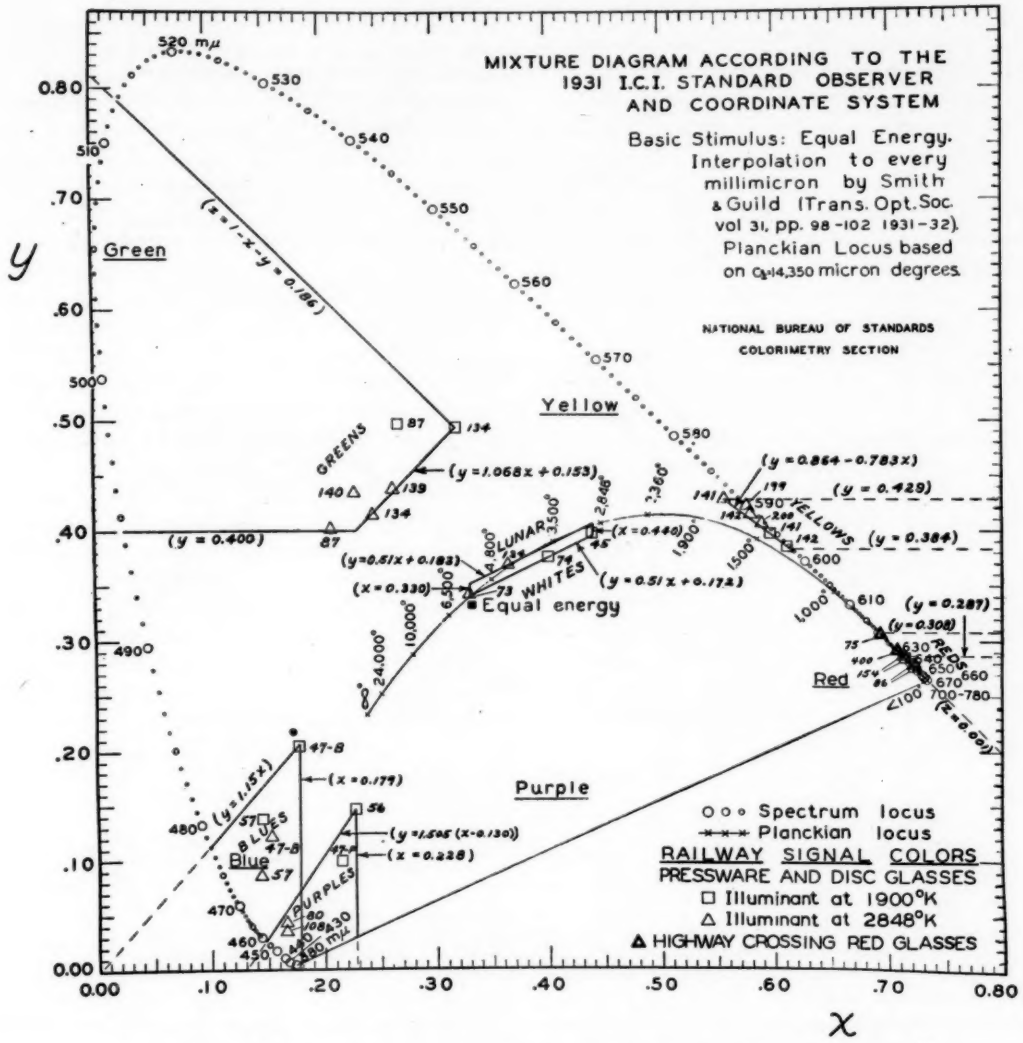

FIG. 7. ICI chromaticity (mixture) diagram showing the permissible areas for railroad signal colors and the locations of the standard limit glasses for the designated illuminants, according to AAR Signal Section Specification 69-40.

plete absorption in the blue and violet, and sharp transition in the green or yellow green. Occasionally, however, a melt is obtained with an "unsharp cut-off," as it is usually called, and glass 200 is a good example. Note the transmission extending in measurable amounts through the blue and violet.

This glass had been selected and marked as standard before it was suspected that it failed in this respect to be typical. The fact that the failure was not detected by inspection shows that it is not of much importance. However, the value of the blue coordinate, z, is larger than normal and affected the tolerance established for such glasses, as is illustrated below.

Other differences among the curves correlate with the type of glass—whether heat-resistant or non-heat-resistant, whether designed for elec-

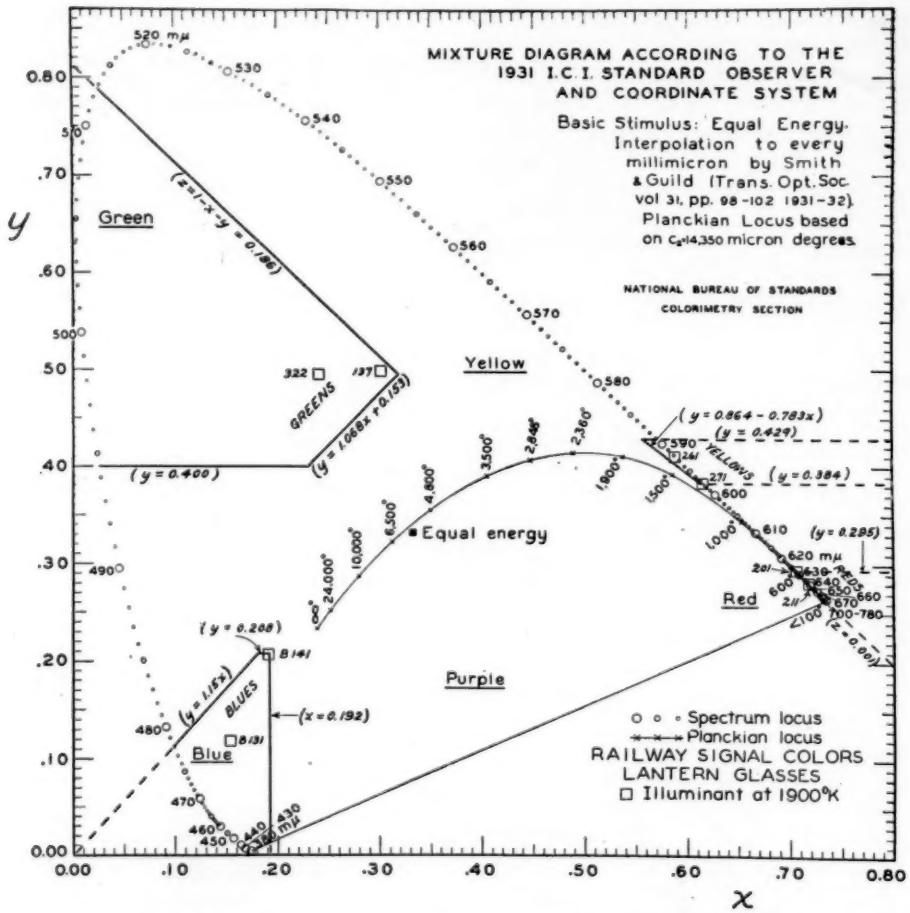

FIG. 8. ICI chromaticity (mixture) diagram showing the permissible areas for hand lantern colors and the locations of the standard limit glasses for 1900°K illuminant, according to AAR Signal Section Specification 59-39.

tric or kerosene illuminant, and so on. Correlation may also be noted between the curves of Figs. 1 to 6 and the luminous transmissions and chromaticity coordinates given in Table IV and illustrated in Figs. 7 and 8.

IV. CHROMATICITY LIMITS OF RAILROAD SIGNAL COLORS

The chromaticities of the standard glasses defining the limits of acceptable colors for railroad signaling were given in Table IV, above. Reference to the 1931 ICI standard observer and coordinate system, in terms of which these values of x, y, and z were derived, was given in Section II, above. Reference has also been made to three illuminants used in the railroad signal standardization—"kerosene" or 1900°K, 2360°K, and "electric" or 2848°K. A word of explanation as to the choice of these illuminants is appropriate.

As noted in the previous paper, the original illuminant used in railroad signaling was the kerosene flame. In time this illuminant was replaced by the electric lamp for many signaling purposes, but in hand lanterns and in certain other installations the kerosene flame is still used. In some cases the same type of glass can be used and will give an acceptable signal with either

illuminant; in others, different types have to be used for each illuminant.

The color temperature of the kerosene flame varies with the type of burner. That of the signal burners is close to 1900°K. It therefore seemed appropriate to adopt 1900°K as the color temperature of the kerosene illuminant for railroad signaling, and spectral distributions of energy of the "blackbody" or Planckian radiator at this temperature have been used in this work in all computations of luminous transmission and chromaticity for the kerosene illuminant.[15]

The "electric" illuminant used in railroad signaling, at least one very common type, has a color temperature of approximately 2680°K. Since the rated color temperatures of most gas-filled lamps are higher than this, however, it seemed wise to adopt a higher color temperature for specification purposes. In this way, certain of the limit glasses would not fail to give colors meeting the specification when the color temperature of the illuminant happened to be somewhat higher than 2680°K. It seemed appropriate, therefore, to select 2848°K, the color temperature and spectral energy distribution adopted in 1931 by the International Commission on Illumination and known as ICI illuminant A.[7]

One other illuminant is of importance in railroad signal standardization, namely, 2360°K. This is the color temperature at which the T_{AAR} scale of luminous transmissions was established, as explained in the previous paper and illustrated in Table I of the present paper. This color temperature is of little importance to the chromaticity specifications, being intermediate to the other two; but values of x, y, and z are given to indicate the course of the chromaticity loci for the respective glasses as the color temperature of the illuminant is varied over the range from 1900 to 2848°K. These loci are illustrated in Fig. 9.

[15] As is well known, the exact values of radiant energy for any specified temperature depend on the value of C_2 in Planck's equation

$$E_\lambda = \frac{C_1\lambda^{-5}}{[\exp(C_2/\lambda\theta)]-1}.$$

For continuity with the published reports and specifications we are retaining the value of $C_2 = 14{,}350$ micron-degrees. Recent values have varied from 14,320 on the International temperature scale to 14,360 as recommended by Wensel, J. Research Nat. Bur. Stand. **22**, 375 (1939) RP 1189. All values of color temperature in this paper are based on $C_2 = 14{,}350$.

It is apparent that in defining areas of acceptable chromaticity on the chromaticity diagram, one is interested primarily only in the particular illuminant-glass combinations used in actual signaling practice. For example, certain of the glasses are designed for use only with kerosene illuminant and certain others for use only with electric illuminants; see Table II. Others like the non-heat-resisting (non-HR) yellows and certain greens are used with both illuminants. A specification for signal colors (illuminant-glass combinations) must take this into account.

The areas finally selected and in current status are shown in Fig. 7, which is a reproduction of the diagram illustrating Part A of AAR Signal Section Specification 69–40 for signal colors excluding kerosene hand lantern globes, and in Fig. 8, which is a reproduction of the corresponding diagram in specification 59–39 for kerosene hand lantern globes. Large scale sections of parts of Fig. 7 are shown also in Figs. 10 to 12.

In each of Figs. 7 and 8[16] may be noted (1) the spectrum locus from 380 to 780 mμ, (2) the Planckian locus from <100°K to ∞°K, (3) the equations defining the straight lines bounding the areas of permissible chromaticities, and (4) the point for each standard glass plotted for illuminant at 1900° and/or 2848°K.

A chart similar to Fig. 7 has appeared in the various AAR Signal Section specifications beginning in 1935, these being based on recommendations made to the signal engineers in 1933, as already noted. The chart shown in Fig. 8 first appeared in 1938 in 59–38. The areas from specification 69–38 were incorporated so far as possible into 59–38, deviations being made only where the standard glasses selected for 59–38 would not fall within the areas already selected for 69–38.

Some discussion should be given regarding the reasons leading to the choice of boundary lines in Fig. 7. Obviously, simplicity of specification will be secured by using lines parallel to the x or y axes, at 45° to these axes, or passing through the origin. Where possible, then, such boundaries were used; deviations from such boundaries were

[16] In Figs. 7, 8, and 13, certain of the numbers designating the blue and purple glasses carry the auxiliary designations B or P, as engraved on the glasses. In the rest of the paper, however, these letters have been omitted, since they seemed unnecessary and somewhat confusing.

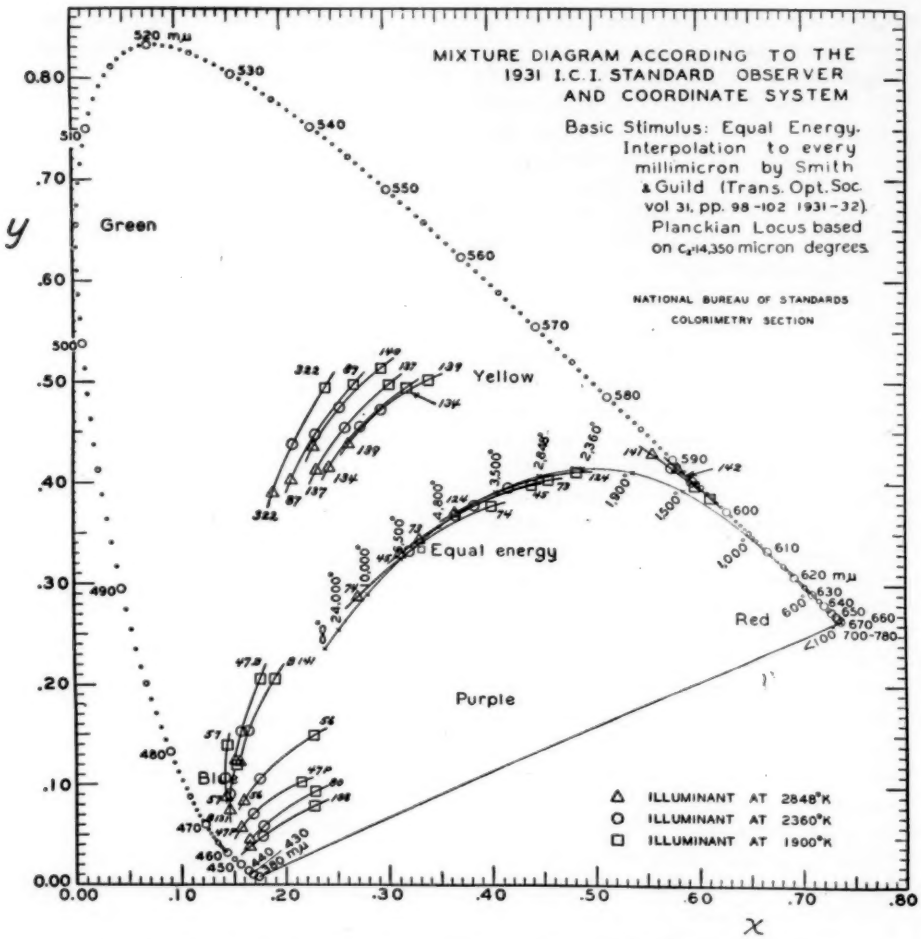

FIG. 9. ICI chromaticity (mixture) diagram showing variations in the chromaticity (x, y) of signal glasses as the illuminant is changed from 1900°K through 2360°K to 2848°K.

made only when it seemed desirable for special reasons. These boundaries of Fig. 8 and Specification 69–40 are considered in detail in the following sections.

For red colors.—The area is defined by the lines $y = 0.308$ (for highway crossing red) or 0.287 (for other reds) and $z = 0.001$. Reference to Table IV shows that these values of y represent closely the yellow limits for the respective reds as given by the respective standard limit glasses when used with electric illuminant. Kerosene illuminant gives lesser values of y for the same glasses, which is satisfactory. The z limit is a rather liberal tolerance for selenium red glasses, but there is no need to make it more restrictive. Here as with most of the other colors, the spectrum automatically forms one boundary of the permissible area, but this spectrum line does not need to be specified. It may be noted that the parts of the areas inclosed by the spectrum and the line joining the red and violet ends of the spectrum are indicated by continuous lines. The extensions of these lines beyond the spectrum are indicated by dashed lines.

For yellow colors.—The green limit is based upon the value of y for glass No. 141 with electric

illuminant and the red limit is close to the value of y for glass 142 with kerosene illuminant.[17] Values of y for the disk glasses with electric illuminant are between these limits. The third boundary line, $y=0.864-0.783x$, restricting the weakness of yellow signal colors, was selected to give maximum deviations from the Planckian locus while still passing all of the glasses. It may be noted from Fig. 7 that this area falls midway between the red and yellow regions of the diagram rather than within the yellow region. Signals which are truly yellow rather than orange are unsuitable because they are found to be more confusible with bare incandescent lights and lunar white signals than are the railroad signal yellows.

For green colors.—The yellow limit is based on glass 134 with kerosene illuminant and the blue limit is close to 87 with electric illuminant. The somewhat arbitrary boundaries, $z=0.186$ and $y=0.400$, would intersect near the illuminant region and there seemed to be no adequate reason for attempting to secure boundary lines that might theoretically be slightly more appropriate. It might be argued, for example, that the line $z=0.186$ should be replaced by a line connecting the point for glass 134 (with kerosene illuminant) with the 1900° point on the Planckian locus. However, since transmission limitations prevent glasses from being accepted which would plot much closer to the spectrum than do glasses 87 and 140, the exact course of these two boundary lines is of little importance. Simplicity of specification justifies those chosen. The weakness boundary of the acceptable area for green signal colors, $y=1.068x+0.153$, was determined by glass 134 for the two illuminants, all of the other points falling within this area.

For blue and purple colors.—These may well be considered together. The most important fact in this connection is that blue and purple signals are not differentiated by the engineer by their chromaticities in the usual sense. Note in Fig. 7 that the "purple" signals do not fall in the purple region of the diagram. The blue must not be mistaken for green or lunar white or for the dichromatic purple; the purple must be recognized as a dichromatic (red-blue) signal.[18] It therefore seemed adequate to use the simple triangular areas shown, the overlapping being of no consequence.

For lunar white colors.—These must be differentiated from yellow, green, and blue. The yellow boundary is based on glass 45 with kerosene illuminant, the blue boundary on 73 with electric illuminant. Green and purple limits, as such, were not selected.[19] It was believed that manufacturing tolerances were well represented by the glasses selected. Accordingly, the rhomboidal area shown in Fig. 7 was specified. An equally satisfactory specification can be prepared in terms of deviations from the Planckian locus combined with blue and yellow limits; and this has been done with aviation colors.[20]

The signals using kerosene illuminant and covered in Specification 69–40 are differentiated in railroad purchase specifications from the kerosene hand lantern globes covered in Specification 59–39. As already noted, the areas of 59–39, Fig. 8, were made identical with those of

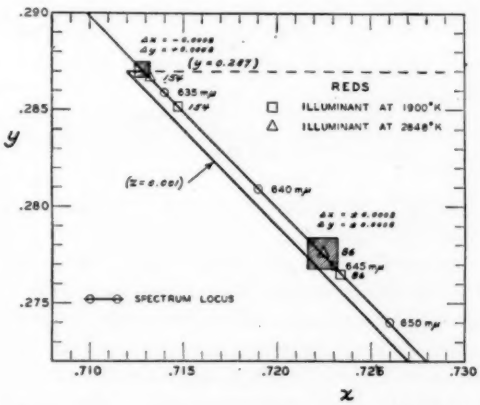

FIG. 10. Large scale section of Fig. 7 showing (dark areas) the tolerances in x and y permitted in glasses certified as duplicates of standard limit glasses designated as red, for pressed ware and disks.

[17] This boundary was originally at $y=0.386$, given by 142 with kerosene illuminant, but was later lowered to $y=0.384$ to include the red limit of lantern yellow No. 271.

[18] Because of chromatic aberration of the lens system of the human eye, the dichromatic image is normally a red center with a blue halo or surround, though this will vary with the vision of the observer. Neither blue nor purple are used as long range, high speed signals.

[19] Lunar white glasses are "cobalt blue" glasses. Experience indicates that important deviations in the green or purple directions do not occur in the manufacture of such glasses.

[20] Army-Navy Aeronautical Specification: Colors; Aeronautical Lights and Lighting Equipment; AN-C-56 (1942).

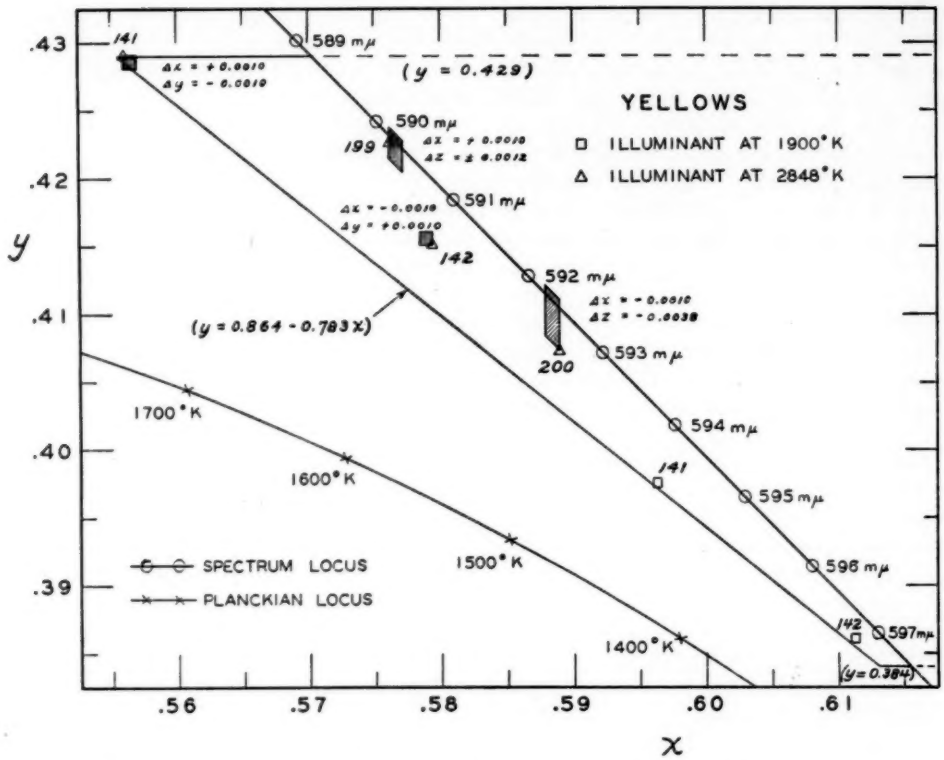

FIG. 11. Large scale section of Fig. 7 showing (dark areas) the tolerances in x and y, or x and z, permitted in glasses certified as duplicates of standard limit glasses designated as yellow, for pressed ware and disks.

69–40, Fig. 7, so far as possible. The following points may be noted.

For red lantern-globe colors.—The yellow limit is given by $y=0.295$. The color perception of signal red varies toward yellow as the intensity of the signal is increased. Lantern reds are low intensity signals, and a yellower signal was accordingly considered permissible. (The yellow limit of highway crossing red, $y=0.308$, is permitted to be still yellower. This signal is not viewed by the engineer and there is no yellow, except possibly those of bare illuminants, with which it can be confused.)

For yellow lantern-globe colors.—The area specified is identical with that in 69–40, the red limit being determined by glass 271, as already noted.

For green lantern-globe colors.—The area specified is identical with that in 69–40.

For blue lantern-globe colors.—The red transmission cannot be eliminated from heat-resisting blue glass as effectively as from the other kind of blue glass; see Table III. Accordingly the x boundary had to be moved from 0.179 to 0.192, necessitating an additional boundary ($y=0.208$) to restrict the weakness of the colors.

Based on considerations discussed in this section and consistent with the diagrams shown in Figs. 7 and 8, specifications of chromaticity were established and included in Parts A of AAR Signal Section Specifications 69–40 and 59–39. In addition to the chromaticity limits specified in these parts A, there are given also the minimum limits of luminous transmission for signal glassware, expressed in terms of the T_{AAR} scale. Since the intensities of the illuminants are otherwise independently specified, the luminous transmissions of the glassware serve as an adequate specification of the intensities of the signal colors.

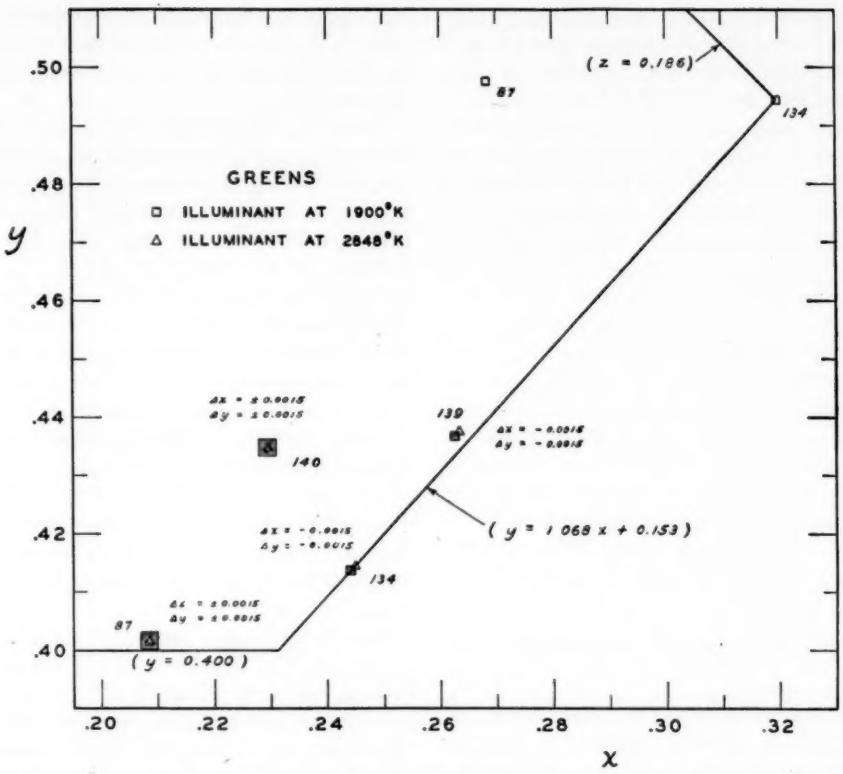

FIG. 12. Large scale section of Fig. 7 showing (dark areas) the tolerances in x and y permitted in glasses certified as duplicates of standard limit glasses designated as green, for pressed ware and disks.

The following quotations are taken from the respective specifications:

From AAR Signal Section Specification 69-40, Part A.

"*5. Red.*—(*a*) Three types of red ware are used: (1) pressed ware, for which the value of T_{AAR} shall be not less than 85, (2) thin polished disks, for which the value of T_{AAR} shall be not less than 115, and (3) highway crossing roundels, for which the value of T_{AAR} shall be not less than 220; in cases (1) and (2) the value of y shall be not greater than 0.287, and in case (3) not greater than 0.308, and in all three cases the value of z shall be not greater than 0.001.

"*6. Yellow.*—(*a*) Two types of yellow glass are used: (1) the non-heat-resisting type, for which the value of T_{AAR} shall be not less than 130, and (2) the heat-resisting type, designed for use in thin disks with electric illuminant, which must have one surface depolished and for which the value of T_{AAR} need not be specified; in both cases the value of y shall be not greater than 0.429 nor less than 0.384, also not less than $0.864-0.783x$.

"*7. Green.*—(*a*) Two types of green glass are used: (1) the non-heat-resisting type, for which the value of T_{AAR} shall be not less than 150, and (2) the heat-resisting type, designed for use in thin polished disks with electric illuminant, for which type the value of T_{AAR} shall be not less than 138; in both cases the value of y shall be not less than 0.400 nor less than $1.068x+0.153$, and the value of z not less than 0.186.

"*8. Blue.*—(*a*) the value of T_{AAR} shall be not less than 75; the value of x shall be not greater than 0.179, and the value of y not greater than $1.15x$; the value of T_r/T_w shall be not greater than 0.008.

"*9. Purple.*—(*a*) Two types of purple glass are used: (1) that designed for use with kerosene illuminant, for which type the value of T_{AAR} shall be not less than 73 and the value of T_r/T_w not less than 0.116, and (2) that designed for use with electric illuminant, for which type the value of T_{AAR} shall be not less than 30 and the value of T_r/T_w not less than 0.187; in both cases the value of x shall be not greater than 0.228, and the value of y not greater than $1.505(x-0.130)$, nor shall the value of T_r/T_w be greater than 0.240.

"*10. Lunar White.*—(*a*) Two types of lunar white glass are used: (1) that designed for use with kerosene illuminant, for which type the value of T_{AAR} shall be not less than 80, and (2) that designed for use with electric illuminant, for which type the value of T_{AAR} shall be not less than 147; in both cases the value of x shall be not greater than 0.440 nor less than 0.330 and the value of y not greater than $0.51x+0.183$ nor less than $0.51x+0.172$."

From AAR Signal Section Specification 59-39, Part A.

"*5. Red.*—(*a*) The value of T_{AAR} shall be not less than 140; the value of y shall be not greater than 0.295; and the value of z not greater than 0.001.

"*6. Yellow.*—(*a*) The value of T_{AAR} shall be not less than 200; the value of y shall be not greater than 0.429 nor less than 0.384, also not less than $0.864-0.783x$.

"*7. Green.*—(*a*) The value of T_{AAR} shall be not less than 125; the value of y shall be not less than 0.400 nor less than $1.068x+0.153$, and the value of z not less than 0.186.

"*8. Blue.*—(*a*) The value of T_{AAR} shall be not less than 55; the value of x shall be not greater than 0.192 and the value of y not greater than 0.208 nor greater than $1.15x$; the value of T_r/T_w shall be not greater than 0.015."

V. TOLERANCES FOR CERTIFYING DUPLICATES OF STANDARD LIMIT GLASSES

Parts A of Specification 69–40 and 59–39 serve as a fundamental specification of the colors (chromaticities and intensities) of railroad signals. As such they are adequate for use by any standardizing laboratory equipped to make accurate spectrophotometric measurements or otherwise to derive accurate colorimetric data based on the 1931 ICI standard observer and coordinate system.

They are not adequate and suitable, however, for use by most glass manufacturing plants or by inspectors of signal glassware. For such purposes it is apparent that duplicates of the standard limit glasses must be available to the manufacturer or the inspector, so that by simple colorimetric and photometric comparisons it can quickly be determined if any glassware in question comes within the tolerances given in Parts A of the specifications.

In a continuation, therefore, of the work already undertaken by the three cooperating agencies, it was agreed that Corning Glass Works should prepare duplicates of the standard limit glasses which would be measured by the National Bureau of Standards and, if found satisfactory, certified and issued to those in need of such glasses.

One of the most important questions to be decided in this connection was the magnitude of the tolerances to be adopted in accepting and certifying duplicates of the standard limit glasses. If too liberal tolerances were adopted, one manufacturer might be at a disadvantage relative to another by having a smaller total range within which he must keep his product. If the tolerances were too small, the difficulties of securing a sufficient number of acceptable duplicates would unduly prolong the work, and the time at which the specifications could be promulgated and the duplicates issued would be seriously delayed.

The matter was actually decided largely on the basis that the smallest tolerances would be established and used which would still permit Corning Glass Works to prepare a suitable number of duplicates with reasonable time and cost. This was effective and practical even if not ideally scientific.

Space does not permit a detailed description of apparatus and procedures used in examining or measuring the hundreds of duplicate glasses submitted. Many of these details may be found in Nat. Bur. Stand. Reports 6 and 7, to which reference has already been made. The following points may be briefly noted:

1. Colorimetric comparisons were made and relative values of luminous transmission were determined mostly by means of a Schmidt and Haensch Martens photometer with a simple 2-part 6° photometric field. Most of the work was done with a color temperature of 2360°K. This was necessary in the determination of T_{AAR} and T_r/T_w, and the field brightnesses were such that it was preferable to work at this color temperature for the chromaticity examinations. Care was taken to ascertain that all duplicates accepted would be valid for illuminants at 1900°K or 2848°K, consistent with the tolerances to be given in the specifications. Duplicates and standards were so nearly identical that important questions of heterochromatic photometry did not arise.

2. Various methods were used to determine accurately the small chromaticity differences involved.

(1) With the selenium red glasses, where melt number has little significance, a large number of duplicates for each standard were examined and a sample found having a chromaticity differing from the standard by about the amount finally adopted in the specification, the magnitude of this tolerance being always sufficient to include the desired number of acceptable duplicates. The differences in x or y of this tolerance-limit sample from the standard were determined spectrophotometrically.

(2) In certain cases—for example, with some of the blues and purples—duplicates of the standard were prepared from the same melt or piece. In such cases no deviations of chromaticity from the standard could be detected, experience indicating that the duplicates were all well within the tolerances finally adopted.

(3) In some cases Lovibond glasses of low number could be inserted in series with the standard until the duplicate was matched in chromaticity. Computation then gave the differences in x or y from the standard. By interpolation all chromaticities within the tolerance could be measured by means of the Lovibond glasses.

(4) The chromaticities of the diffusing ("depolished") disk yellow duplicate glasses were determined relative to the polished non-diffusing standards on a color-temperature comparator having a large Lummer-Brodhun trapezoidal field, with special filters and diffusing plates. Chromaticity matches were made by varying the color temperature of one of the standard lamps.

3. Values of T_r/T_w for the blue and purple glasses were derived from measurements made on the Martens photometer with illuminant at 2360°K and with a dark limit red glass (duplicate of 86) over the ocular. This in effect limits the determinations to the visual range 650 to 770 mμ, as called for in the specifications. As with measurements of T_{AAR}, values were determined relative to a closely similar standard, whose value of T_r/T_w had been determined spectrophotometrically.

4. The uniformity of the values of T_{AAR} over the surface of each 2-inch-square duplicate glass was determined by measurements made at four different regions relative to that at the center. Practically all glasses but the selenium reds and yellows were found to be uniform in transmission; that is the values did not differ from those at the center by as much as 1 percent of the value. All of the red glasses, and the disk-yellow and lantern-yellow glasses, are "selenium" glasses, whose color varies with heat treatment. On this account they are usually non-uniform in transmission and chromaticity. This was not tested for the 1-inch-diameter disk-yellow duplicate glasses. For the 2-inch squares prepared as duplicates for lantern yellows and for all of the reds, however, the uniformity of luminous transmission was measured. Satisfactory chromaticity duplicates were too rare to permit any rejections for non-uniformity. Instead, the variations of T_{AAR} are given in the certificate, with a note that such variations are usually accompanied by chromaticity variations—the higher the transmission the yellower (or greener) the glass. These variations of transmission often were several percent of the value at the center. Tolerances of Δx and Δy, as finally adopted and given in Parts B of AAR Signal Glass Specifications 69–40 and 59–39, are given in Table V. The tolerances for reds 154 and 86, for yellows 141 and 142 and yellows 199 and 200, and for greens 134 and 87 and greens 139 and 140, are illustrated in the large scale sections of the chromaticity diagram shown in Figs. 10 to 12. Corresponding diagrams for the other glasses and colors can be plotted from the data of Tables IV and V if desired.

TABLE V. Maximum chromaticity deviations permitted for glasses certified as duplicates of standard limit glasses for railroad signaling, AAR Signal Section Specifications 69-40 and 59-39.

Color designation	Number of glass	Color temperature of illuminant °K	Chromaticity coordinates, x, y, z, and maximum deviations, Δx, Δy, Δz, for glasses and illuminants indicated					
			x	Δx	y	Δy	z	Δz
Red	154	2848	0.7132	−.0008	0.2867	+.0008	0.0000	0.001*
	86	2848	.7224	±.0008	.2776	±.0008	.0000	.001*
	75	2848	.6927	+.0008	.3072	−.0008	.0001	.001*
	400	2848	.7088	±.0008	.2912	±.0008	.0001	.001*
	201	1900	.7051	+.0008	.2948	−.0008	.0001	.001*
	211	1900	.7178	±.0008	.2822	±.0008	.0000	.001*
Yellow	141	2848	.5560	+.0010	.4291	−.0010	.0149	——
	142	2848	.5794	−.0010	.4151	+.0010	.0056	——
	199	2848	.5762	+.0010	.4226	——	.0012	±.0012
	200	2848	.5889	−.0010	.4073	——	.0038	−.0038
	261	1900	.5873	+.0010	.4107	−.0010	.0020	——
	271	1900	.6151	−.0010	.3843	+.0010	.0006	——
Green	134	2848	.2448	−.0015	.4145	−.0015	.3407	——
	87	2848	.2084	±.0015	.4016	±.0015	.3899	——
	139	2848	.2634	−.0015	.4376	−.0015	.2990	——
	140	2848	.2295	±.0015	.4348	±.0015	.3357	——
	137	1900	.3025	−.0015	.4974	−.0015	.2001	——
	322	1900	.2415	±.0015	.4942	±.0015	.2643	——
Blue	47	1900	.1783	−.0020	.2049	−.0020	.6168	——
	57	1900	.1458	+.0020	.1387	+.0020	.7154	——
	141	1900	.1916	−.0030	.2070	+.0010 −.0020	.6014	——
	131	1900	.1543	±.0015	.1187	±.0015	.7270	——
Purple	56	1900	.2280	−.0020	.1475	−.0020	.6245	——
	47	1900	.2158	+.0020	.1000	+.0020	.6842	——
	80	2848	.1661	±.0005	.0426	−.0010	.7913	——
	108	2848	.1658	±.0005	.0352	+.0010	.7990	——
Lunar white	45	1900	.4395	−.0015	.3981	±.0010	.1624	——
	74	1900	.4005	−.0020	.3766	+.0020	.2229	——
	124	2848	.3654	±.0010	.3688	±.0010	.2658	——
	73	2848	.3308	±.0010	.3426	+.0020	.3266	——

* This tolerance is given in Part A of the signal glass specifications. In effect it limits the tolerances of ±0.0008 in x and y for the dark limit glasses, as shown in Fig. 10.

All limit glasses must conform to the restrictions imposed by Parts A of the two specifications. This is noted in Table V for the red glasses by giving the tolerance $\Delta z = 0.001$; see also Fig. 10. Other similar restrictions may be noted for yellow 141, Fig. 11; green 134, Fig. 12; and for others.

Probably in most cases the tolerances shown in Table V are logical in terms of the coordinates used. Where a standard glass is a chromaticity limit it is logical that duplicates of this glass be allowed to deviate towards but not away from the optimum chromaticity. For example, with yellow glass 141, which is a pale and green limit, the restrictions of Table V (combined with Part A) insure that duplicates of this glass can deviate only in the red and more saturated directions.

In other cases the logic of the situation is violated. This is true for red 154. The logical tolerances are $\Delta x = +0.0008$, $\Delta y = -0.0008$, as are given for reds 75 and 201. With red 154, however, practically all of the close duplicate

glasses available were in the region $x=0.7132-0.0008$ and $y=0.2867+0.0008$. To expedite the work, therefore, the tolerances shown were adopted, it being considered that a value of $y=0.2875$ did not exceed the value of $y=0.287$ given in Part A of the specification.

Corresponding "reasoning," based on expediency rather than idealism, resulted in some of the other tolerances shown. However, the time involved in preparing samples and making measurements was greatly shortened, and the issuance of the specifications expedited, by permitting such deviations from what in many cases might be considered a more ideal set of tolerances.

In addition to restrictions on the chromaticities of the duplicates of the standard limit glasses, as shown in Table V, it was also desirable to set tolerances on the values of T_{AAR} for such glasses, and of T_r/T_w for the blue and purple glasses. Accordingly, values were adopted as shown in Table VI. The magnitudes of the tolerances were determined largely by the same considerations as were effective for the chromaticity tolerances. In these cases, however, it is no disadvantage to any manufacturer if the T_{AAR} value of his glass is more or less than that of another manufacturer. This is because the manufacturer is required to have an "approved photometer," by means of which the value of T_{AAR} for any glassware can be actually measured from the known (certified) values of T_{AAR} engraved on his duplicate limit glasses. In other words, this certified glass is a transmission *standard*, not a transmission *limit*, and the minimum values of T_{AAR} given in Parts A and C of the specifications are the ones that apply to his glassware. This is taken care of in the specifications by the following note:

"It may be noted that in some cases a certified dark limit glass may have, in accordance with this table (Table VI) a value of T_{AAR} slightly less than that given in Parts A and C of this specification; this does not, however, invalidate Parts A and C, which must be met by all glasses to be used in railroad signaling."

VI. EXPRESSION OF RAILROAD SIGNAL COLORS IN A UNIFORM-CHROMATICITY-SCALE COORDINATE SYSTEM

As already noted, the 1931 ICI coordinate system has become a more or less universal language in which the chromaticities of colors may be expressed in terms understood and used by a great majority of workers in colorimetry, both in this country and abroad. As such, it is useful and adequate to define chromaticities and to express tolerances for specifications in a manner similar to that used in the railroad signal specifications as described in this paper.

This coordinate system suffers from one defect, however, in that equal distances in different parts of the diagram, or equal distances in different directions on the same part of the diagram, do not correspond accurately to equally perceptible differences in chromaticity as judged by the average observer. This matter has been considered by various investigators[21] who have in turn proposed "uniform-chromaticity-scale" triangles or coordinate systems and with a considerable measure of success. However, there are great difficulties in the way of obtaining a satis-

TABLE VI. Maximum deviations of luminous transmission on the AAR scale, T_{AAR}, and of red to total luminous transmission, T_r/T_w, both for 2360°K, permitted for glasses certified as duplicates of standard limit glasses for railroad signaling, AAR Signal Section Specifications 69-40 and 59-39.

Color designation	Type	Values of T_{AAR} Light limit	Values of T_{AAR} Dark limit	Values of T_r/T_w* Light limit	Values of T_r/T_w* Dark limit
Red	except highway crossing	170±15	100± 5	—	—
	highway crossing	310±30	220±20	—	—
	lantern	250±15	145± 5	—	—
Yellow	non HR	215±10	160± 5	—	—
	disk	**	**	—	—
	lantern	300±15	250±15	—	—
Green	non HR	205±10	150± 5	—	—
	disk	190±10	138± 5	—	—
	lantern	185±10	127± 5	—	—
Blue	—	130± 5	75± 3	0.008±0.001	0.000+0.001
	lantern	125± 5	56± 3	.014± .002	.008± .002
Purple	kerosene	130± 5	73± 3	.120± .010	.160± .010
	electric	40± 3	30± 2	.190± .020	.220± .020
Lunar white	kerosene	122± 5	80± 4	—	—
	electric	200±10	147± 5	—	—

* For blue and purple glasses only.
** No values specified.

[21] See references 721–731 of chapter VII, "Quantitative Data and Methods for Colorimetry," of the forthcoming report of the OSA Committee on Colorimetry, J. Opt. Soc. Am. **34**, 633 (1944).

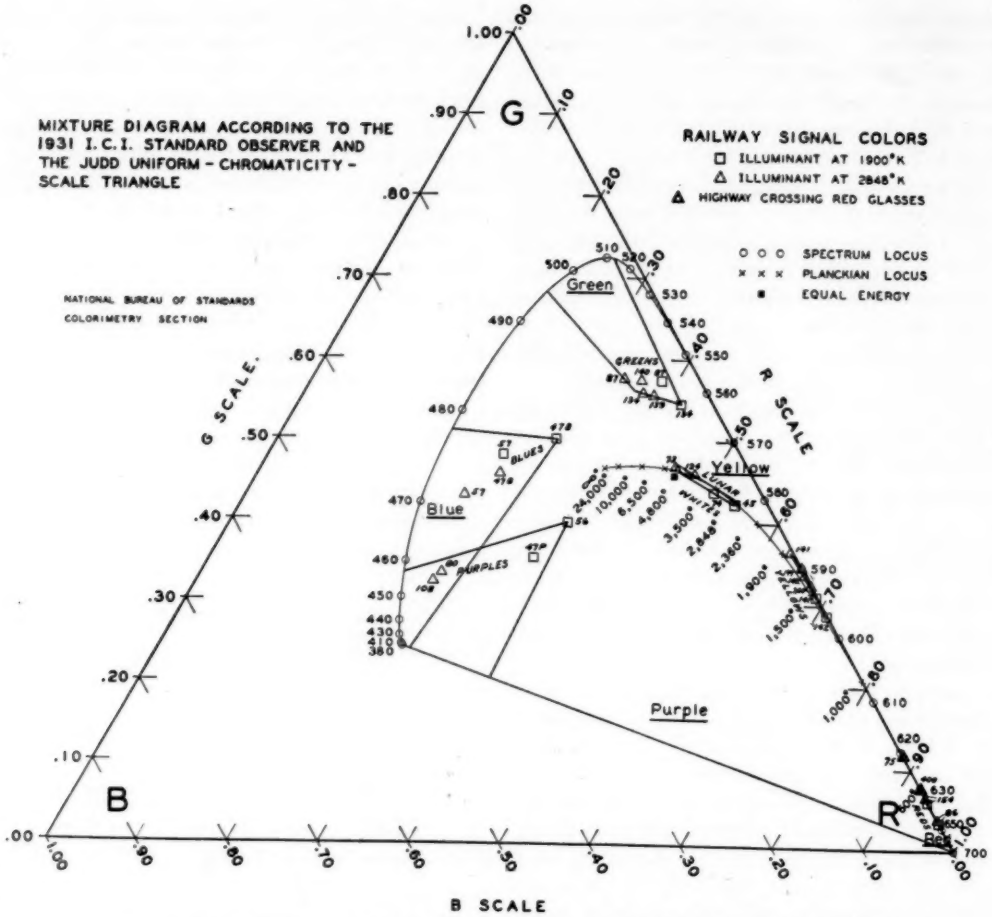

FIG. 13. Transformation of the data of Fig. 7 to the Judd uniform-chromaticity-scale triangle. Equal distances in this coordinate system are more nearly representative of equally perceptible differences in chromaticity than in the ICI coordinate system.

factory coordinate system of this kind. Aside from the question whether any plane surface will give such uniform chromaticity scales, it is known that different systems would be necessitated for differing observing conditions. For example, the same coordinate system will not give equal chromaticity scales for both (1) extremely small sources such as are used in most signal installations and (2) large fields such as are commonly used in color matching of textiles or in comparing samples with Munsell standards.

While therefore such investigations are of great interest and may eventually lead to revision of the ICI coordinate system, there is no prospect that such revision will be seriously attempted for a long time. In the meantime, however, it is often instructive to express results in one of these systems to obtain a better idea as to the relative perceptibility of the various colors involved.

The first attempt at transformation of the ICI coordinate system to a uniform-chromaticity-scale coordinate system was made by Judd.[22] Since the data on which this transformation was based were obtained with a small (2°) photometric field and with dark surrounds it is to be

[22] Deane B. Judd, "A Maxwell Triangle Yielding Uniform Chromaticity Scales," J. Research Nat. Bur. Stand. **14**, 41 (1935) RP 756; J. Opt. Soc. Am. **25**, 24 (1935).

expected that this system would be a good approximation to that applicable to signal colors under the usual signaling conditions. In fact, no certain improvement in Judd's system for such a purpose has been made.

In this uniform-chromaticity-scale system the coordinates, x, y, z, are replaced by new coordinates r, g, b. As in the ICI system, these coordinates represent fractional parts of reddish, greenish, and bluish primaries, but the primaries are different. Judd's paper should be consulted by those interested in a further understanding of this system and of the method of transformation involved.

In Fig. 13 are shown, on the Judd uniform-chromaticity-scale triangle, essentially the same data as are shown in Fig. 8. The following points may be noted:

1. The distance from the red to the yellow signal colors is the same as that from the yellow to the green signal colors.

2. The separation of the lunar whites from the yellows and greens is approximately equal.

3. There is considerable diminution of the area representing permissible green signal colors from the corresponding areas for the other colors.

All of these effects are, of course, consistent with the changes from circles of uniform radius on Judd's triangle to ellipses of varying size, eccentricity, and orientation on the ICI diagram, which have been illustrated elsewhere.[23] They show, furthermore, the excellence of the signal colors selected by the engineers, particularly the choice of the red, yellow, and green signals used for long range signaling on the main lines where the trains move at high speed.

VII. AAR SIGNAL SECTION SPECIFICATIONS FOR SIGNAL GLASSES AND HAND LANTERN GLOBES

References to AAR Signal Section Specifications 69–40 for Signal Glasses (Exclusive of Kerosene Hand Lantern Globes) and 59–39 for Kerosene Hand Lantern Globes have already been made in the preceding sections of the paper in connection with discussion of the data on which parts of these specifications were based.

Each of these specifications consists of three parts, A, B, and C. The purposes of these parts are indicated in the following quotations from Specification 69–40:

"Part A of this specification is for the purpose of defining the minimum values of luminous transmission for signal glasses and the limits of chromaticity for signal colors produced by illuminant-glass combinations."

"Part B of this specification is for the purpose of defining the maximum deviations from the standard limit glasses, both in transmission and chromaticity, to be permitted in glasses certified as duplicates of the standard limit glasses."

"Part C of this specification is for the purpose of providing approved colored roundels, lenses, disks, and slides for railroad signaling, to describe the materials, and specify the appliances and appurtenances necessary to make the required tests and inspection. It sets forth specific detail requirements representing modern signal practice recommended for new installations and for the replacement of existing material when general renewal or replacement becomes desirable."

Similar purposes are given for Parts A, B, and C of 59–39.

The three parts of these specifications illustrate the threefold division which a complete color specification often necessarily takes—(1) the fundamental definition of the colors, with tolerances, as in Part A; (2) the fundamental definitions of the working standards, with tolerances, as in Part B; (3) the methods of use and application of the working standards, as in Part C.

Consideration of Parts A and B of Specification 69–40 and 59–39 has already been given in Sections IV and V of the present paper. These two parts relate entirely to colorimetric or photometric specifications. Part C gives various information pertinent to a purchase specification, as stated in the "Purpose" above, and in addition specifies the transmission tests and the chromaticity tests which are made possible by the certified duplicate limit glasses.

The following excerpts from Part C of 69–40 described these tests, and indicate the part which the National Bureau of Standards takes in the certification of duplicate limit glasses.

[23] Deane B. Judd, "Estimation of Chromaticity Differences and Nearest Color Temperature on the Standard 1931 ICI Colorimetric Coordinate System," J. Research Nat. Bur. Stand. **17**, 771 (1936) RP 944; J. Opt. Soc. Am. **26**, 421 (1936).

TABLE A. Minimum values of luminous transmission on the AAR scale, T_{AAR}.

Color designation	Pressed lenses and roundels, and cut or pressed slides	Polished flat disks
Red	85	115
Red (highway crossing)	220	
Yellow	130	(Depolished on one side)
Green	150	138
Blue	75	
Purple (kerosene)	73	
Purple (electric)	30	30
Lunar white (kerosene)	80	
Lunar white (electric)	147	

"3. Apparatus and appurtenances for testing

(a) Certified limit glasses

"1. Certified light and dark limit glasses, calibrated by the National Bureau of Standards, Washington, D.C., shall be made available by the Seller for use of the Purchaser while conducting tests. These certified glasses shall serve to define both the proper luminous transmissions of the glasses to be tested and the proper chromaticities of the resulting signal colors as hereinafter provided.

(b) Photometer

"1. An approved photometer shall be made available by the Seller for use of the Purchaser while conducting tests. The illuminant used for measurements shall have a color temperature between 2360°K and 3000°K, and with no samples in the beams the two halves of the photometric field shall have the same chromaticity.

"*Note.*—1. Vacuum tungsten lamps or gas-filled tungsten lamps with white[24] bulbs should give the specified color temperature, if operated at normal voltage.

"2. The 1908 specification established spectrophotometric values for a glass in each of the six colors, having a chromaticity and a transmission value approximately midway between the respective values for the light and dark limits. Each of these glasses was given as arbitrary value of 100 percent for use as a standard in laboratory and routine photometry. By means of these standard glasses, the present photometric scale for measuring the transmission of all colored signal glasses was established. This practice is continued except that the 100 percent pressed standards have been superseded by the standard limit glasses in the form of 2 in. polished squares.

"4. Tests and inspection

(e) Transmission test

"1. The Purchaser shall measure the transmission T_{AAR} of each glass, using the above specified photometer and illuminant and respective certified limit glasses whose values of T_{AAR} are engraved thereupon. A glass shall not be acceptable whose value of T_{AAR} is less than the respective minimum value given in Table A.

"*Note.*—Either of the following additional tests shall be applied to the blue and purple glasses: (1) a red glass (approximately equivalent to the dark limit red glass) shall be placed over the eye-piece of the photometer. The transmission of blue glasses for this red light shall be not greater than that of the light limit blue glass, and similarly the transmission of purple glasses for this red light shall be not less than that of the dark limit purple glass; or (2) an incandescent lamp shall be viewed through a red glass (approximately equivalent to the dark limit red glass). The test glass and the limit glass, placed edge to edge, shall be rapidly alternated in position in the beam between the lamp and the eye. The transmission of the blue glasses so examined (for red light) shall appear not greater than that of the light limit blue glass, and similarly the transmission of purple glasses so examined (for red light) shall appear not less than that of the dark limit purple glass.

(f) Chromaticity test

"1. The Purchaser shall compare the chromaticity of each glass with that of the respective certified limit glasses, using for this purpose the above specified photometer and illuminant. The comparisons shall be made with brightnesses matched. A glass shall not be acceptable if its chromaticity fails to meet either of the following requirements:

"(*a*) The hue shall be not outside the hue limits given by the respective certified limit glasses; except that (1) for red glasses, only the yellow limit need be tested, and (2) for disk green glasses, the blue limit shall be given by the dark limit pressware (non heat-resisting) green glass.

"(*b*) The saturation shall be not less than that given by the respective certified light limit glasses; except that, for lunar white glasses, the saturation shall be not outside the saturation limits given by the respective certified limit glasses.

"5. Marking

(a) Certified limit glass marking

"1. Each certified limit glass (2-in. square or 1-in. diameter disk) shall be permanently engraved with the serial number by the maker and further permanently engraved by the National Bureau of Standards with the serial number, the designation, the value of T_{AAR}, the N.B.S. test number, and the date.

"*Note.*—In all cases, the engravings may be verified, and additional information regarding the certified limit glasses obtained, from the N.B.S. Certificates for the glasses which shall be made available to the Purchaser by the Seller."

Since the formulation of these specifications, over 200 duplicate limit glasses, with certificates, have been issued by the National Bureau of Standards to various applicants, some in foreign countries.

Success in carrying through the program of railroad signal glass standardization which has been described in the previous and present papers has resulted in large measure from the generous cooperation of Corning Glass Works. All of the

[24] That is, inside-frosted incandescent lamps.

field tests conducted by the signal engineers in their selection of colors and glasses have been held at Corning. Special acknowledgment is due in this connection to Dr. H. P. Gage, under whose supervision these tests were conducted and who has had charge of the preparation of the hundreds of glasses prepared during this work, either for study or for issuance as certified duplicate glasses.[25] The authors have also had the valuable technical advice of Dr. Gage throughout the work.

In conclusion, reference should again be made to the progressive spirit of the railroad signal engineers, which has kept them among the leaders in the use of the best techniques in the selection of signal colors and in the formulation of purchase specifications based on colorimetric data. Credit for the present satisfactory status of the railroad signal glass specifications is due largely to (1) the chairmen of AAR Signal Section Committee VI, Mr. J. C. Mock, under whose supervision the initial program was started, and Mr. A. S. Haigh, who carried on after the retirement of Mr. Mock and brought the specifications to their present status, and (2) the secretaries of the Signal Section, Mr. H. S. Balliet at the start of the work and his son, Mr. R. H. C. Balliet, in whose office the preparation and revision of the specifications have been handled.

[25] Many of the glasses certified by the National Bureau of Standards have been prepared by Corning Glass Works without charge. Under present arrangements such glasses may be purchased from Corning Glass Works for a nominal amount and certified by the National Bureau of Standards at regular test fee schedules. The Bureau will also accept suitable glasses from other companies for test, with the regular charge for certification or rejection.

Proceedings of the Thirtieth Annual Meeting of the Optical Society of America

HOTEL PENNSYLVANIA, NEW YORK, NEW YORK, OCTOBER 18, 19, AND 20, 1945

WITH wartime travel restrictions ended it was not surprising that registration for the thirtieth Annual Meeting reached the record-breaking total of 532. The program, which included special sessions on Infra-Red Spectroscopy, Emission Spectroscopy, Vision, and Color, presented a strong appeal.

INVITED PAPERS

At this meeting, a new plan was adopted of introducing sessions for contributed papers on selected topics by an invited paper on the same subject which summarized the developments of the past few years. These invited papers prepared the audience for the more highly specialized contributed papers which followed.

The meeting opened on Thursday with a session on Infra-Red Spectroscopy. Dr. Joseph R. Downing introduced the subject with a paper entitled "Infra-Red Spectroscopy in Industry." Tracing the history of the development of the theory of molecular vibrations from 1905, when Coblentz published his great "Investigations of Infra-Red Spectra," down to the modern quantum theory he pointed out the increasing fruitfulness of interpretation of the spectra in terms of molecular structure. He then described present-day automatic apparatus for recording infra-red spectra with particular reference to an instrument which records density directly. Considerable emphasis was placed on the importance of developing the technique of sample preparation. He concluded with an enumeration of the many important applications of infra-red analysis in chemical and biochemical research and in industrial process control.

Dr. George R. Harrison introduced the second session on Friday with a paper on "Emission Spectroscopy." Stating that the concave grating has now "arrived," he listed its advantages and indicated the direction of research to overcome its disadvantages. He named "sources" as the weakest link in the development of spectrographic analysis, and recommended that considerable effort be directed toward the achievement of greater stability and better control. Particularly he favored the investigation of sources under vacuum and under controlled pressures. Reviewing the recent development of direct-reading instruments, he pictured a "linear iconoscope" as a future means of observing and measuring spectra. He concluded with an announcement that tables of intensities are being compiled by Meggers and Scribner and that the M.I.T. wave-length tables are to be extended.

Dr. George Wald introduced the session on Vision, Saturday morning, with a paper on "Basic Factors in the Spectral Sensitivity of Human Vision." Dr. Wald pointed out that the spectral sensitivity of human vision is governed, not only by the characteristics of the rods and cones of the retina, but also by the pigmentation of the lens and macula. The interplay of these factors had been examined by measuring the absolute threshold of vision in the region between 365 and 750 millimicrons.

The pigment present in the human macula had been extracted and examined spectrophotometrically. It is apparently a hydroxycarotinoid or xanthophyll, probably lutein or leaf xanthophyll itself, $C_{40}H_{54}(OH)_2$. When photopic luminosity data of the central retina are examined carefully in the region from 450 to 580 millimicrons, they show clear indications of the presence of absorption bands due to the macular pigmentation.

The spectral sensitivity of peripheral rods and cones had been measured in lensless (aphakic) eyes. After removal of the lens, the sensitivity of the aphakic eye is very high in the violet and ultraviolet. On the average, aphakic observers are about one thousand times more sensitive than normal observers to light at 365 millimicrons. This fact was dramatically demonstrated by tests which an aphakic observer performed in competition with the audience. The most convincing of these was the reading of

small letters on a Snellen chart illuminated by ultraviolet light when the room was so dark that the audience was unable to see the chart at all.

The session on Color, opening on Saturday afternoon, was introduced by Dr. David L. MacAdam whose paper was entitled, "Some Basic Ideas in Color Measurement." He presented some carefully prepared and striking demonstrations based on a lecture delivered in 1871 by James Clerk Maxwell. (Maxwell's lecture, entitled "On Color Vision," was published in the *Proceedings of the Royal Institution of Great Britain.*[1]) The spectral absorption of colored materials was demonstrated as were the effects of mixtures of colored light. The conceptual and experimental basis for three-color specifications were discussed and demonstrated. In conclusion, examples were shown of the fulfillment of Maxwell's forecast of the most fruitful method of representing the results of studies of color perception. The need for further work on the discrimination of colors with results represented in Maxwell's three-color space, as well as in Young's triangle, was emphasized.

[1] J. C. Maxwell, Proc. Roy. Inst. 6, 267 (1871).

ANNUAL BANQUET

There were 240 members and guests at the banquet on Friday evening, at the conclusion of which President Pfund introduced the newly elected officers. The principal feature of the evening was the award of the Frederic Ives Medal for 1945 to Dr. W. W. Coblentz.

BUSINESS SESSION

A business session was held on Saturday morning, President Pfund presiding. The reports of the Secretary, Treasurer, and Editor of Publications for the fiscal year 1944 were presented and accepted. The President announced that plans were being made to hold the next meeting of the Society in Cleveland, Ohio, on March 7, 8, and 9, 1946.

CONTRIBUTED PAPERS

The abstracts of the contributed papers are appended.

MEETING OF THE BOARD OF DIRECTORS

A meeting of the Board of Directors was held on Wednesday, October 17. The minutes of this meeting appear on page 808 of this issue.

PROGRAM OF SESSIONS

(Titles and Abstracts of Papers)

Session on Infra-Red Spectroscopy

1. Invited paper, entitled "Infra-Red Spectroscopy in Industry," by JOSEPH R. DOWNING, *E. I. duPont de Nemours & Company, Inc.*

2. Production and Properties of Nickel Bolometers. FRANK G. BROCKMAN, *Socony-Vacuum Oil Co., Inc.**

As a part of the development of an alternating-current bolometer, a method for the production of very thin nickel ribbons (and incidentally, nickel foil) has been developed. Ribbon filaments have been prepared which are as thin as 0.1 micron. These filaments appear to possess the properties of bulk nickel. Certain properties of these filaments have been studied and are described. The method is not restricted to nickel, bismuth ribbons having been prepared by the same procedure.

* Now with the Richmond Hill Laboratories of the North American Philips Company.

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3. Alternating-Current Bolometer for Infra-Red Spectroscopy. C. H. SCHLESMAN* AND F. G. BROCKMAN.†

An alternating-current bolometer system has been developed for detecting and recording radiant energy in infra-red spectroscopy. Almost constant use over an extended period dictates certain improvements which are pointed out. The useful sensitivity is limited now by fluctuations originating in the power supply to the bolometer bridge.

* Director, Research and Development Division, Socony-Vacuum Oil Co., Inc.
† Now with the Richmond Hill Laboratories of the North American Philips Company, Dobbs Ferry, New York.

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H. H. Scott, Proc. I.R.E. 26, 226 (1938).
S. E. Miller, Electronics 14, 27 (Nov. 1941).

4. Recording Infra-Red Analyzers for Butadiene and Styrene Plant Streams. N. WRIGHT AND L. W. HERSCHER, *The Dow Chemical Company.*

A simple compact instrument is described which analyzes various organic mixtures by automatic measurement of

absorption of infra-red radiation. Optically the instrument consists of a double beam system employing a single source of radiation, a split lens or mirror, a sample cell, and various filters through which one or both beams may pass, and two electrically opposed detectors upon which the beams are focused. Selectivity of wave-length is provided by the filters and by detectors having selectivity absorbing radiation receivers similar in principle to those of Pfund.[1] The detectors are two opposed arms of an a.c. excited bolometer made of fine nickel wire imbedded in a selectively absorbing medium. A vacuum tube amplifier working on the bolometer output actuates a potentiometer-recorder which automatically restores the bridge balance and in the same operation records the analysis of the sample. Successful operation of these instruments on continuous analysis of plant streams of butadiene-butene gas mixtures and of styrene-ethylbenzene liquid mixtures is detailed.

[1] A. H. Pfund, Science **90**, 326 (1939).

5. A Versatile Infra-Red Spectrograph. ROBERT A. OETJEN, *Beacon Research Laboratory of the Texas Company, Beacon, New York.*

An infra-red spectrograph having sufficient flexibility to permit a wide variety of investigations is described. Its main characteristics follow. Any one of two prisms and two gratings, mounted on a table rotated by a large worm wheel, may readily be put into the path of the collimated radiation. A foreprism spectrometer is built into the instrument in such a way that it may be by-passed. The spectrograph case and the source housing are evacuable. Moving parts in the evacuated chamber are controlled through induction and Autosyn types of motors. This permits control, entirely electrical, from a semi-portable unit outside the spectrograph. The widths of the slits are automatically varied so that the output of the radiation detector thermocouple is approximately the same for all spectral regions if no absorbing material is in the path. The radiation detector is a rapid-response evaporated thermocouple whose output is amplified by a vacuum tube amplifier. A pulsating thermocouple output voltage is obtained by interrupting the radiation at the entrance slit by a rotating shutter. Shutters of metal, mica, and sodium chloride are used to minimize the effect of scattered radiation. To adjust the frequency of the shutter to match the sharply tuned amplifier, the rotational speed of the shutter disk is controlled through a synchronous motor driven by a variable-frequency power supply. A thyratron-operated calibration flasher is used to put reference lines on the photographically recorded spectra. The housing in which the Nernst glower is mounted is equipped with windows so that it may be divided into compartments to serve also as a vapor cell. This unit carries a mounting designed to locate a liquid cell precisely.

6. Two Bilateral Spectrograph Slits. HERMANN ROEMER, *Harrison H. Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan,* AND ROBERT A. OETJEN, *Beacon Research Laboratory of the Texas Company, Beacon, New York.*

Details of two bilateral slits designed for use in an infra-red spectrograph are described. The widths of the slit openings may be continuously varied from 0 to 4 millimeters in one case and from 0 to 12 millimeters in the second case. The designs permit reproducible fine control of these widths.

7. The Design and Construction of Rapid-Response Thermocouples for Use as Radiation Detectors in Infra-Red Spectrographs. L. C. ROESS AND E. N. DACUS, *Beacon Research Laboratory of the Texas Company, Beacon, New York.*

The design and construction of a rapid-response vacuum thermocouple for use in an infra-red spectrograph is described. The thermocouple is made by condensing 600–1000A thick layers of Bi and Sb, which overlap slightly to form the hot junction, on a 400–500A thick film of Formvar. This film is stretched over a glass form having an opening under the hot junction. The hot junction is blackened with gold evaporated in H_2 at 2–4 torr. (1 torr = 1 mm Hg.) The thermocouple is intended for use with radiation interrupted at frequencies between 1 and 5 hertz. (1 hertz = 1 cycle per second.) It is shown that the signal-to-noise ratio of the thermocouple, defined as the ratio of the interruption frequency component of its output to the square root of its resistance, is the only criterion of its goodness, and that in an infra-red spectrograph a single junction thermocouple has a greater signal-to-noise ratio than a multi-junction thermopile. An important operation in the thermocouple construction is the use of a glow discharge before condensation of each metal to reduce the thermocouple resistance by factors of 5 to 10. Such a thermocouple has a resistance of between 20 and 50 ohms, a d.c. sensitivity of 6–7 microvolts per 10^{-4} watt cm^{-2}, and an output under radiation interrupted at 7 hertz of not less than one-half the d.c. value.

8. Vacuum Tube Amplifier for Measuring Very Small Alternating Voltages. L. C. ROESS, *Beacon Research Laboratory of the Texas Company, Beacon, New York.*

The design and construction of a low frequency vacuum tube amplifier capable of detecting $5 \cdot 10^{-10}$ volt is described. The amplifier is intended to measure the alternating output of a rapid-response thermocouple in an infra-red spectrograph, the incident radiation being interrupted at frequencies between 1 and 5 hertz. (1 hertz = 1 cycle per second.) The inherent noise level of the amplifier is less than the thermal noise of the thermocouple. This low amplifier noise level is attained by use of an excellent high gain input transformer, by careful selection of the first vacuum tube and operating its heater at low current, by use of inverse feedback, and by use of two power supplies, one for the heaters in series and a second for the plate and screen potentials, both of which have very good electronic voltage regulators. This noise level is further reduced by the use of inverse feedback and twin-T resistance-capacity networks to give a narrow and variable band width. The amplifier is operated from the a.c. power line. It feeds a short period galvanometer whose entire swing is recorded photographically so that the record has the appearance of a modulated carrier wave. A portable microammeter fed

from a vacuum tube voltmeter is used as a visual monitor of the output. A simple photoelectric test signal generator is described, and typical records show the amplifier noise as well as its output for input signals as low as $6 \cdot 10^{-10}$ volt. The effect of too narrow a band width on the recording time of an absorption spectrum is discussed briefly and is illustrated by water vapor spectrum records.

9. An Infra-Red Gas Analyzer. WALTER S. BAIRD, *Baird Associates, Cambridge, Massachusetts.*

The infra-red gas analyzer described by Pfund[1] and recently improved by N. Wright has been further developed for analysis and industrial control. This instrument may be described as an infra-red "meter" of high resolving power and zero dispersion. It is of particular value for organic gas mixtures whose components are isomers or otherwise so closely related as to make usual methods of analysis extremely difficult. This instrument will replace the infra-red spectrometer for many applications, especially for continuous analysis and control because of its inherent simplicity and ruggedness. The principle used involves two infra-red beams from a 10-watt filament source. Any difference in energy of these two beams is indicated by a bolometer bridge and amplified for an output meter or recorder. A filter of the compound to be measured is placed in one infra-red beam in such a manner as to sensitize the instrument only to this compound in the sample. The sample cell covers both beams. Front surface mirrors are used and rocksalt completely eliminated. The proper use of these analyzers requires a knowledge of all the gases present in the mixture and the ranges of variations and partial pressures expected. Four models of the gas unit assembly have been developed in order to cover a large range of analytical problems. A portable model with a 50-cm sample cell is under development for the determination of quantities of certain gases present in small quantities in air.

[1] A. H. Pfund, Science **90**, 326 (1939).

10. Infra-Red Analysis of Carbon Monoxide and Butadiene Systems. H. M. O'BRYAN, *Baird Associates, Cambridge, Massachusetts.*

The infra-red gas analyzer has been calibrated with pure gases and then used to analyze synthetic mixtures of CO–CO_2 and of butene, butadiene, and ethylene. These systems were chosen as examples of simple and relatively complex gas mixtures. The achievement of maximum sensitivity with stability and a minimum of interference depends largely on choice of gas pressures, cell lengths, filters, and combination of light and electrical balance. The Model B unit with the filter cell filled with CO_2 gave an error in CO_2 determination which amounted to one-hundredth of the CO present in the sample. Because of the relatively strong infra-red absorption of CO_2 this instrument had lower discrimination in the determination of CO in the presence of CO_2. The Model C unit having a 30-mm interference cell gave negligible interference on similar mixtures. The infra-red spectral transmission curves of butadiene, butene, and ethylene showed serious overlapping absorption between butene and butadiene for a butadiene rich mixture, indicating the necessity of the Model C analyzer with butene in the interference cell. This decreased the interference of butene on butadiene determination by a factor of five. The interference due to ethylene could be reduced to one part in twenty. The pressure range for which sensitivity becomes a maximum depends on cell length and the extinction coefficient.

11. A Double Monochromator for the Infra-Red. DONALD K. COLES, *Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.*

Probably the most satisfactory method known of eliminating stray radiation is the use of a double monochromator. Such an instrument has been designed and built with especial attention given to reproducibility of intensity measurements and ease of operation. The intermediate slit, between the two component monochromators, is wider than the entrance and exit slits of the double monochromator, so that resolution of the double monochromator depends on the width of the entrance and exit slits only. It is thus possible to use collimating mirrors which are sectors of a sphere or "on axis" sectors of a paraboloid, since the aberration of coma introduced by the first component monochromator is cancelled in the second component monochromator.[1] The prism arrangement of the double monochromator is such that the resulting dispersion at the exit slit of the double monochromator is twice the dispersion of either of the component monochromators. A series of slits of fixed width are used to ensure reproducibility of slit width. These may be interchanged by pushing a button and are automatically changed during a spectral run. The Littrow mirrors of the component monochromators are mounted on the same table, which automatically rotates at a varying speed to conform to the varying slit widths.

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12. Transmittance and Reflectance of Germicidal Energy. MATTHEW LUCKIESH AND A. H. TAYLOR, *Lighting Research Laboratory, General Electric Company.*

The increasing use of ultraviolet energy in the region of λ2537 for the destruction of air-borne bacteria and sterilization of water, etc., enhances the need for extensive data on the transmissive and reflective properties of materials. Much of the research effort of the Lighting Research Laboratory is devoted to the study of these properties and the development of a scientific foundation for the utilization of this energy from modern sources. In addition to a discussion of the properties of materials, some effects of these upon the effectiveness of germicidal energy will be presented.

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13. Spectrophotometrical Determinations of Nucleic Acids and Nucleases in Cerebrospinal Fluids after Cerebral Concussion.* M. SPIEGEL-ADOLF, H. T. WYCIS, AND E. A. SPIEGEL, *Departments of Colloidal Chemistry and Experimental Neurology, Temple Medical School, Philadelphia, Pennsylvania.*

Previously reported studies[1] have been extended to 15 clinical cases with concussions and 11 patients with other nervous disorders. (Altogether 50 samples with over 900 single spectrophotograms.) In concussion the cerebrospinal fluids (*CSF*) show an absorption band in ultraviolet light with a peak at about 2650A, besides the normal end absorption. These changes become manifest a few hours after the injury and last several weeks. This absorption type is characteristic for purin and pyramidin, especially since the interference of proteins or barbiturates could be excluded. All control cases with purely functional disorders showed end absorption only. The appearance of nucleic acids in the *CSF* after concussion is in agreement with histological findings of chromatolysis.[2] The special absorption band of the *CSF* of concussed patients disappears within 3 hours at room temperature, even under sterile conditions but not if the sample is kept on ice. A corresponding solution of animal nucleic acids (Difco) keeps unchanged at room temperature at least for 19 hours. If such a solution is mixed with a *CSF* of a concussed patient, the nucleic acid solution loses its specific absorption power after 5 hours. These changes can be demonstrated by colorimetric methods likewise, e.g., by the Dische reaction,[3] which permits quantitative colorimetric determinations of nucleic acids. The nucleic acid solution gives a positive Dische reaction also after 19 hours of standing at room temperature, while this test becomes negative after 5 hours in a mixture with the *CSF* from a concussed patient. Normal *CSF* does not affect either the Dische reaction or the spectrographic behavior of the nucleic acid solutions. The identification of the nuclease active in *CSF*'s of concussed patients is being attempted. It could be ascertained that it is different from ribonuclease, which does not affect the Dische reaction of animal nucleic acid solutions.

* Aided by a grant from the J. and M. Markle Foundation.
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14. The Ultraviolet Absorption Spectra and Other Physical Data for Cardiolipin, a New Phospholipid, and Lecithin Isolated from Beef Heart. M. O'L. CROWE AND A. WALKER, *Division of Laboratories and Research, New York State Department of Health, Albany.*

Cardiolipin, a serologically active phospholipid has recently been isolated from beef heat and purified.[1] Spectrophotometric studies of cardiolipin and lecithin from beef heart have been undertaken in continuation of studies of cephalin, lecithin, and selected beef heart antigens that were published in 1936.[2] These studies are of importance because of the antigenic activity of some of these substances in the serologic tests for syphilis. Cardiolipin represents a class of phospholipids that has not previously been obtained in a pure state. "Chemically the substance may be described as a complex phosphatidic acid. On alkaline hydrolysis, it yields unsaturated fatty acids, chiefly linoleic, and a water-soluble phosphoric acid that breaks down on further hydrolysis with acids into glycerophosphoric acid and glycerol."[3] The curve for a sample of cardiolipin covers the range between λ2150A and 3700A. There is a sharp maximum at λ2348A and indications of selective absorption in the range of λ2600–2750A, and near λ3000A where conjugated unsaturated fatty acids having two, three, and four double bonds, respectively, show absorption. An estimation of the proportions of conjugated diene, triene, and tetraene material that is present in cardiolipin has been made from spectroscopic data.[4–6] For such ultraviolet conjugation assays, we have compared our curves with certain published standard curves for linoleic,[4] eleostearic,[7] and parinaric acids[8] which are representative of fatty acids having two, three, and four conjugated, unsaturated double bonds, respectively. There is evidence that acids of two conjugated, unsaturated double bonds are present in greater abundance (in one sample, about 5.7 percent) than conjugated triene and tetraene acids which occur in very small amounts. Exposure to ultraviolet light for the time necessary for making spectrograms did not destroy the serologic activity of cardiolipin. Some observations of fluorescence and of crystal forms and aggregates of crystals from solutions obtained by passing cardiolipin through a chromatograph of Al_2O_3 are presented.

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[4] L. J. N. van der Hulst, Rev. Trav. Chim. **54**, 639, 644 (1935).
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15. A Lens to Supplant the Spectrograph Slit. CARL KING, *Harry W. Dietert Co., Detroit, Michigan.*

It is readily apparent that a narrow origin of light must be provided in a spectrograph or allied instrument where the utmost of resolution is desired. The classic solution to this problem is to provide a slit consisting of carefully machined stainless metallic jaws mounted in parallelism at the desired spacing. This slit of itself constitutes the desired narrow light origin. In this paper will be described a different means of obtaining the effect of a narrow origin of light. A cylindrical quartz lens of short focal length is used. The axis of the cylindrical lens surface is set parallel to the slit which the lens replaces. The lenses used have been of the concave variety, having negative focal lengths of one-half centimeter and one centimeter, respectively. The name "pseudo-slit" has been applied to these lenses when used for this purpose. The pseudo-slit "sees" a macroscopic light source as a narrow line. Very narrow lines are readily obtained. Means are also described for obtaining lines of adjustable width by magnifying an aperture of fixed width.

16. An Electrical Computing Machine for Solving Simultaneous Equations. T. D. MORGAN AND F. W. CRAWFORD, *Research Department, Phillips Petroleum Co.*

A brief description of a method of iteration for solving simultaneous equations of the type encountered in absorption spectroscopy will be followed by a demonstration of an electrical computer designed to carry out these operations. In this computer the steps of the method of iteration are carried out by the addition and subtraction of electric potentials in potentiometric circuits. Provision is made in the computer to take care of transient negative values which sometimes appear when solving equations by the method of iteration. Eleven component equations can be solved in a few minutes with an accuracy of about 0.5 absolute percent. The computing machine solution plus one arithmetic cycle by method of iteration will improve this accuracy somewhat.

Session on Emission Spectroscopy

17. Invited paper, entitled "Emission Spectroscopy," by GEORGE R. HARRISON, *Massachusetts Institute of Technology.*

18. A Combination Arc-Spark Source for Magnesium Analysis. V. J. CALDECOURT AND J. L. SAUNDERSON, *The Dow Chemical Company.*

A compact arc-spark unit is described. The arc is interrupted so that it is on one-half second out of each second, resulting in improved reproducibility in burning the sample. A condenser charged to nearly 3000 volts is discharged through the sample gap at the rate of 120 times per second to provide the spark source. Advantages in reduced radio-frequency radiation and improved stability of analytical calibrations are obtained.

19. Analysis for Beryllium in Magnesium Alloys. T. M. HESS, L. G. REINHARDT, AND E. L. MCLAUGHLIN, *Dow Chemical Company.*

The analysis for small amounts of beryllium in magnesium alloys containing aluminum is difficult and time consuming. This paper describes a spectrographic procedure for making this determination. The alloys are dissolved in sulfuric acid, a known amount of an internal standard is added to the solution, and a drop of the solution is loaded on unimpregnated graphite electrodes. After the salt has dried on the ends of the graphite electrodes, it is excited in the same spark discharge circuit used to analyze the magnesium alloys in the solid state. The method has a sensitivity of one part per million and has been used successfully up to concentrations of one percent.

20. Spectrographic Determination of Boron in Steel.* CHARLES H. CORLISS AND BOURDON F. SCRIBNER, *National Bureau of Standards.*

The determination of small amounts of boron (0.0001 to 0.02 percent B), added to steel to improve certain physical properties, has presented a difficult problem to the analyst. In view of the tedious nature of the chemical determination of boron, an investigation of the applicability of spectrographic methods was carried out, culminating in the detailed study of three spectral excitation methods and in the certification of six NBS spectrographic standards for boron in steel. The first excitation method, the high-voltage a.c. arc, was found useful with thin rod self-electrodes for determinations in the range 0.0005 to 0.02 percent boron, with an average deviation of 4 percent from the mean for repeated determinations of concentrations above 0.001 percent boron. The electrode size, shape, and mounting for the test samples and standards are maintained constant to obviate the marked effect of variations in the heat conduction from the points of discharge on the electrodes. This method of excitation, when applied to the point-to-plane electrode technique, showed an unsatisfactory limit of detection of 0.003 percent. The second excitation method, an over-damped condenser discharge (multi-source unit) permitted determinations to be made with the point-to-plane technique in the range 0.0006 to 0.02 percent boron, with a precision equivalent to that of the first method. The third method was devised in order to detect and determine boron at concentrations as low as 0.0001 percent. In this method a 10-ampere d.c. arc is employed under conditions adjusted to maintain low level excitation, thus reducing the interference of an iron spark line (Fe II) with the strongest boron line. The method is applied to the analysis of flat pieces of steel, accurately cut to a pre-determined size, using a counter-electrode of graphite which is cored and filled with sodium sulfite. In the course of the investigation, 6 boron steels were prepared and issued as NBS spectrographic standards in two sizes (1) 7/32 in. diameter, 4 in. long and (2) 1/2 in. diameter, 2 in. long, to cover the range 0.0006 to 0.019 percent boron.

* This investigation was sponsored by the War Metallurgy Committee and supported by the Office of Production Research and Development.

21. Spectrochemical Analysis of Lead Base Metals. B. J. BEISEL AND L. J. HIBBERT, *The National Cash Register Company, Dayton, Ohio.*

A procedure is discussed for the control of lead-base type metals with a commercial grating spectrograph. A flat-surface technique involving a chill cast disk sample with a graphite counter electrode is employed. High percentages of tin and antimony are determined. A modified method of film calibration involving the relative intensity of lead lines is discussed. The effects of certain variables and special techniques were investigated. Complete excitation and film developing conditions are given, and analytical curves are shown for the following ranges:

Tin	3.0–10.0 percent
Antimony	10.0–20.0

Tables illustrate the reproducibility and accuracy of results.

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22. A Direct-Reading Spectrochemical Installation. J. L. SAUNDERSON, V. J. CALDECOURT, AND E. W. PETERSON, *The Dow Chemical Company.*

A direct-reading spectrochemical installation, capable of analyzing for ten elements in magnesium alloys, is described. The apparatus is especially designed to control the product by analyzing, in the shortest possible time, samples from the pots before pouring. A new type combination arc and spark source unit is used for sample excitation. A specially constructed spectrograph, consisting of a two-meter grating in an Eagle mounting, has eleven electron multiplier photo-tubes mounted behind exit slits lying in the focal plane. Apparatus for measuring the relative intensity of the spectral lines, power supplies, and recorder complete the instrument. A record, from which the percentages of seven elements may be read from calibrated scales, is available fifty-five seconds after loading the sample electrodes in the clamps. During the time the electrodes are being sparked or arced, the currents from the multiplier photo-tubes are collected in condensers. At the end of the arc or spark period, the condensers are simultaneously discharged through resistors of such magnitude that RC is about five seconds. D.c. amplifiers of unique construction and remarkable stability follow the voltage on the discharging condensers and indicate when the voltage on the condensers becomes equal to that of a standard cell. The *difference* in time required for two condensers having identical RC constants to discharge down to the same voltage is proportional to the log of the ratio of the two charges. The recorder, using electrical marking paper in strip form, measures simultaneously in this manner the intensity of seven spectral lines relative to one internal standard line. The multiplier photo-tubes in combination with the amplifiers and recorder measure the relative intensities with an accuracy of better than 0.5 percent. Repeat analyses on some of the major constituents in magnesium alloys show an average error of about 2 percent of the amount present.

23. A New Two-Meter Grating Spectrograph for Spectrochemical Analysis. M. F. HASLER, *Applied Research Laboratories, Glendale, California,* AND H. W. DIETERT, *Harry W. Dietert Company, Detroit, Michigan.*

A new spectrograph has been designed with the present needs of spectrochemical analysis clearly in mind. It utilizes one or two original reflecting gratings of two-meter radius of curvature mounted on the Rowland circle. One or two cameras each providing a twenty-inch spectrogram can be moved along a sixty-inch arc of the circle to provide an unusually large coverage of a highly dispersed spectrum. A 24,400 line per inch grating provides a first-order dispersion of 5.2A per mm. At this dispersion one camera can photograph 2500A anywhere in the range 1850A to 9200A. A 36,600 line per inch grating provides a first-order dispersion of 3.5A per mm. At this dispersion 1660A can be photographed with one camera anywhere in the range 2100 to 7000A. Second-order spectra of twice these dispersions are also available. A small displacement of the end of the optical bench between two fixed stops allows either grating to be used at a moment's notice. The camera employs 35-mm film on which eighteen spectra may be placed. All masking, selective filtering of certain lines, and film calibration are done by apertures and filters at the camera. A massive aluminum base supports all optical parts of the instrument, including the entire optical bench. This base is supported by a three-point suspension on rubber mounts in a massive sheet steel case. The instrument is so sectionalized that the camera portion can be readily enclosed in a dark room with the optical bench portion extending into the operating room.

24. Some Practical Applications of a Direct-Reading Instrument to Spectrochemical Analysis. M. F. HASLER, *Applied Research Laboratories, Glendale, California* AND H. W. DIETERT, *Harry W. Dietert Company, Detroit, Michigan.*

A direct-reading instrument for quantitative spectrochemical analysis employing bright line spectra has been described by the authors in a previous paper.[1] A greatly improved model employing the principles discussed in that paper has been developed and built. In the present work, this new instrument is described in some detail, particularly as to its mode of operation. To illustrate its general flexibility and ease of manipulation, results obtained with the instrument in the spectrochemical analysis of aluminum and magnesium alloys and steels are shown. The conclusion which may be reached from these examples is that much quantitative spectrochemical analysis of a routine nature which does not involve spectrographic traces of elements, nor basic materials which possess very complex spectra, can be carried out more rapidly and accurately by a direct-reading instrument of this type than by present photographic instruments.

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Contributed Papers on Optics

25. A New Light Balancing Circuit for the Non-Recording Densitometer. R. O'B. CARPENTER, *Baird Associates, Cambridge, Massachusetts.* (*Introduced by John Sterner.*)

The extremely sensitive electron multiplier photoelectric tube is used to obtain a light matching circuit much more sensitive and stable at very low light intensities than the conventional balanced photo-tube circuit. Instead of balancing two ordinary photo-tubes against each other, a single electron multiplier tube is used for the light receiver, the beams to be compared being alternately flashed onto the tube by a rotating interrupter. The electrical circuit is designed to give a null balance when the pulses from the two light beams are equal. Application to and improvements in the non-recording Densitometer reported by W. S. Baird[1] are discussed. The improvements are in sensitivity, stability, rapidity of adjustment and measurement, and response time.

[1] W. S. Baird J. Opt. Soc. Am. **31**, 179–180 (1941).

26. Analytical Solution of the Schmidt System for Finite Conjugate Distances. K. PESTRECOV, *Bausch & Lomb Optical Company.*

In the classical arrangement and its variations[1] the Schmidt system is designed for the object (or the image) at infinity. As was pointed out by Maloff and Epstein,[2] a corrector plate designed for infinity would not yield a satisfactory image quality if the system is used for finite conjugate distances. They also stated that the approximate formulas derived by them would not yield the accuracy required for systems of high relative apertures and that in such cases the accurate method of ray tracing should be used. They did not, however, give the actual procedure for the exact solution. A method that may be used for such a solution was suggested by Benford.[3] Although he stated that an analytical solution would be possible, he preferred to use a graphical interpolation as the final step in his procedure. In this paper a complete analytical solution of the problem is given. The method used is essentially the same as was employed by Lucy for an infinite conjugate distance. It consisted in deriving the condition under which the optical paths of all the rays from the object point are constant for a given system. The condition may be expressed as follows:

$$x^2-2Ax-B=0.$$

In this equation:

x is the excavation needed to equalize the optical path of a given ray; coefficients A and B are determined from the basic parameters of the system (the object distance and image distance, the thickness and the refractive index of the corrector plate) and the slope angle of the ray in the object space.

As in the case of the system for infinity, the solution depends on the selection of a zonal ray of the maximum excavation. For a given magnification the selected ray determines the conjugate distances of the system. Approximations are given which may be used for preliminary determinations of the focal length of system, its relative aperture, and the conjugate distances.

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27. Ray Tracing With Punched-Card Equipment. H. R. J. GROSCH, *Watson Scientific Computing Laboratory, Columbia University.*

The design of complex optical systems, and especially of modern large aperture photographic and microscope objectives, now entails so much ray tracing that it becomes economical to introduce standard punched-card accounting equipment to perform the heavy calculations. Methods are described for tracing meridional and skew rays through plane and spherical surfaces, and the extension of these methods to non-spherical surfaces is indicated. The economy of the method outlined depends largely upon the volume of ray tracing to be performed. Estimates of time per ray surface for typical problems and for various machine installations will be given.

28. Afocal Optical Systems. R. A. WOODSON, *Bell & Howell Company.*

The astronomical and Galilean telescopes are ancient examples of afocal systems. Newer applications make use of the unique magnification properties generally overlooked. An afocal system has a constant lateral and longitudinal magnification for all object distances. Object lines parallel to the axis are imaged as lines parallel to the axis. Object planes perpendicular to the axis are imaged as planes perpendicular to the axis. An afocal microscope enhances depth perception and may be used stereoscopically. Other applications include an autofocus copy camera and a light gatherer for a reflex sight.

29. A Glossmeter for Smoothness Comparisons of Machine-Finished Surfaces. RICHARD S. HUNTER, *National Bureau of Standards.*

A need exists for a rapid and simple means to identify machine-finished surfaces which are so rough that ordinary films of paint will not eliminate the uneven contours. Since shininess is one indication of surface smoothness, a photoelectric glossmeter was tried as a means of meeting this need. It was recognized before this trial was started that it would be necessary to coat all test surfaces with a liquid having low viscosity and surface tension in order to fill microscopic cracks and pores in the surfaces and to cover areas of corrosion. The roughnesses to be identified are approximately a thousand times the magnitude of the smallest irregularities which will affect gloss. A mixture of nine parts carbon tetrachloride and one part light mineral oil proved to be a satisfactory liquid for coating machined steel surfaces before gloss measurement. Within fifteen or twenty seconds after this mixture was poured onto any non-horizontal test surface, the excess liquid had drained off, the carbon tetrachloride had largely evaporated, and an oil-coated surface remained which proved fairly reproducible and stable in gloss. The gloss values of such surfaces were found to correlate quite well with the results of other measurements of surface smoothness upon any set of specimens in which the distances between adjacent tool cuts were roughly the same. A near-grazing angle, 75°, was chosen for the measurement of gloss so that otherwise smooth surfaces on which there were ridges of metal between adjacent tool cuts would be rated low in gloss and therefore rough.

30. Theory of Sheet Polarizers. R. CLARK JONES, *Polaroid Corporation.*

A method of producing a form of light-polarizing sheeting is described, and the results of a theoretical examination of the method are discussed. The method involves the stretching of a sheet of transparent material in which are dispersed needle-like microcrystals which have dichroic properties. The crystals, whose orientation is originally random, acquire a new distribution as a result of the stretching so that they are preferentially aligned parallel with the stretch axis. An expression is obtained for the dichroic ratio (ratio of the two principle absorption coefficients of the sheet) as a function of the stretch ratio and of the dichroic ratio of the microcrystals.

31. Pharmacological Responses of Some Previously X-Rayed Animals and Plants. DAVID I. MACHT, *Division of Pharmacology, Laboratories of the Sinai Hospital and X-Ray Department, Baltimore, Maryland.*

In previous papers the author called attention, that for complete evaluation of drug action, the pharmacologist must have his eye on the four "Dimensions of Pharmacodynamics," namely on the drug itself, the biological test object, the external and ecological conditions, and on the *time* factor.[1-3] In the present research, zoopharmacological experiments were performed on mice. These were treated with various doses of x-rays, and after several days, the toxicity of certain drugs for such mice was compared with the effect of injections of the same drugs on control mice. The results varied with the drugs employed. The M.L.D. of some chemicals for previously irradiated mice was smaller than that for the control animals, while the M.L.D of other drugs was the same for both sets of animals. A third class of drugs, of each one representative only was studied, was less toxic for x-rayed mice than for control mice. *Phytopharmacological* experiments were made by the author's well-known methods on *Lupinus albus*.[4-6] Seedlings from previously irradiated water-soaked seeds, and seedlings which were themselves irradiated after germination, responded differently when grown in solutions of various drugs in plant-physiological saline as compared with growth of control seedlings. Some drugs were more toxic for irradiated plants, while other drugs proved to be less toxic. The findings are altogether of considerable clinical interest in connection with drug therapy of patients receiving large therapeutic doses of x-rays.

[1] D. I. Macht, J. Am. Ph. Assn. **17**, 7 (1928).
[2] D. I. Macht, Med. Rev. **38**, 585 (1932).
[3] D. I. Macht, Sci. Mo. **47**, 34 (1938).
[4] D. I. Macht and M. Livingston, J. Gen. Physiol. **4**, 573 (1922).
[5] D. I. Macht and B. M. Macht, J. Lab. and Clin. Med. **26**, 597 (1941).
[6] D. I. Macht, Science **71**, 302 (1930).

Session on Vision

32. Invited paper, entitled "Basic Factors in the Spectral Sensitivity of Human Vision," by GEORGE WALD, *Biological Laboratories of Harvard University.*

33. Investigations on the Site of Origin of "Blackout" in Man. E. H. LAMBERT AND CHARLES SHEARD, *Mayo Aero Medical Unit and Mayo Foundation, Rochester, Minnesota.*

Blackout is a temporary loss of vision without loss of consciousness which aviators experience when they are subjected to high positive acceleration. In the investigations to be reported, temporary loss of vision was produced at 1 g (gravity) by application of air pressure to the eyeball. When the effective systolic arterial pressure to the eye (the systolic pressure at head level minus the pressure applied to the eye) was 49 to 30 mm of mercury, vision was dimmed; peripheral vision was lost at 32 to 20 and vision was completely lost at 21 to zero. These visual changes were the same in latent period, progress of development, and level of effective blood pressure as in the case of the visual changes produced by positive acceleration on the human centrifuge. Application of 20 to 30 mm of mercury pressure to the eyeball when the subject was exposed to positive acceleration lowered the threshold of acceleration at which visual changes occurred by 1 g. Suction of 30 to 40 mm of mercury applied to the eyeball prevents the occurrence of blackout when man is subjected to high acceleration. These and similar experiments to be reported clearly indicate that the loss of vision which occurs without loss of consciousness during high positive acceleration is of retinal origin.

34. Effects of Anoxia, Oxygen, and Increased Intra-Pulmonary Pressure on Dark Adaptation. CHARLES SHEARD, *Division of Biophysical Research, Mayo Foundation and Mayo Aero Medical Unit, Rochester, Minnesota.*

Data will be presented concerning the relative effects of lack of oxygen on the rod and cone thresholds of dark adaptation and the beneficial effects of oxygen on the threshold levels of certain subjects at relatively low altitude (for example, 7000 feet) and under untoward environmental and physiological circumstances, as well as the general stabilizing action of oxygen. The results obtained on the effects of a series of repeated exposures to light of various intensities and durations, with and without the administration of oxygen and at altitudes ranging from ground level to 15,000 feet, indicate, in general, the favorable action of breathing oxygen on the course of recovery and on the threshold levels of dark adaptation. The data available on the partial pressure of alveolar oxygen at low altitudes when the subject is breathing air and at high altitudes when he is breathing oxygen show that an arterial oxygen saturation of 85 percent on the average will be maintained at altitudes of about 12,000 feet when he is breathing air and at 36,000 feet or thereabouts when he is breathing oxygen. Many subjects demonstrate definite changes in both rod and cone threshold levels under these circumstances. With increased intrapulmonary pressure at high altitudes there should be an increase in the partial pressure of oxygen in the alveoli and therefore a greater uptake of oxygen and hence restoration of, or improvement in, the levels of dark adaptation, dependent on the arterial oxygen saturation. Results of the investigations on the effects of positive pressure breathing (generally 4- or 8-inches water pressure, or 7.5- and 15-mm mercury pressure respectively) on the course and levels of dark adaptation of subjects at altitudes ranging from 35,000 to 45,000 feet will be presented. The data obtained show that the use of increased intrapulmonary pressure with pure oxygen permits of the maintenance of maximal sensitivity to light and of the best levels of rod and cone adaptation which are possible under the conditions imposed.

35. Reading Equipment for Partially Blind People. HERBERT JEHLE, *Jefferson Physical Laboratory, Harvard University.*

There are many partially blind people who are just able to recognize headlines in newspapers. It is a great help to them if a projecting equipment is available, enlarging ordinary print. It will allow them to read at least their

own correspondence and books which they want to look up without waiting till a reader is present. In the past years we used an ordinary opaque projector mounted upside down under the table top in which a square opening is cut, coinciding with the opening of the projector. A set of rollers makes a large glass plate slide over the table top. The book lies upside down on the glass plate. This plate is pushed with the hand of the reader such as to bring successive passages of the book before the opening of the projector. The beam of light, after leaving the projector horizontally, is reflected by a vertical mirror a few feet away and thrown back on a vertical transparent screen located next to the projector. So the reading person looks at the enlarged print seen through the transparent screen and has at the same time the motion of the book under control with his right arm.

36. Sunglasses and Sunglass Lenses. S. DAVIS BRONSON, *Precision Lens Corporation.*

The purpose of this paper is to provide a timely, simple, adequate description of the more popular forms and types of sunglasses and sunglass lenses, for commercial, scientific, and military use. Included in this paper are the more popular types of colored, transparent, light-absorbing glasses, and more completely the forms and tolerances of the lenses used. Likewise, this paper is to provide a ready reference for the standards for popular sunglasses, as to their qualities, absorption and transmission properties, manufacturing tolerances, general and specific applications. The most widely used glasses are: smoke, yellow-amber, yellow-green, and sage green. Smoke glasses were formerly the most popular type used for all general purposes. Today, yellow-amber glasses are used by sportsmen and aviators on dull days and for fog piercing. Yellow-green and sage green glasses are the most popular colors today. These are the most widely commercially advertised. All types of sunglass lenses can be further subdivided into three classes: light, medium, and dark shades.[1] The forms of all types of sunglass lenses can be classified into two general groups, (1) commercial and (2) ophthalmic. In the commercial form we have (*a*) blown or coquille lenses, (*b*) flat, colored window-glass lenses, (*c*) flat, colored, polished plate glass lenses, and (*d*) dropped, colored, polished plate-glass lenses. In the ophthalmic form we have (*a*) dropped, colored, polished plate-glass lenses, and (*b*) optically ground and polished lenses.[2] It is curious to note that there are no definite public standards for the different grades of ophthalmic quality lenses, except for limited and specific specifications on individual forms and types, which vary with different manufacturers. It is likewise the purpose of this paper to record a general set of standards for the various types of sunglass lenses, and to catagorize all such lenses into three groups, (1) high-grade ophthalmic, (2) commercial, and (3) substandard, giving complete descriptions, specifications, tolerances and grading of each form and type.

[1] W. W. Coblenz and R. Stair, U. S. Department of Commerce, "Spectral-Transmissive Properties and Use of Colored Eye Protective Glasses," U. S. Government Printing Office, 1938.
[2] U. S. Department of Commerce, "Ground and Polished Lenses for Sunglasses," Commercial Standard CS78–39, U. S. Government Printing Office, Washington, D. C., 1940.

37. Development of the Heliographic Signaling Mirror. R. S. HUNTER, *National Bureau of Standards.*

A pocket-size mirror will reflect flashes of sunlight readily visible to an observer sometimes as much as ten miles away. Because of this power of a small inexpensive device to attract attention at considerable distances, all branches of the armed services have been equipping life boats, rafts, and floats with heliographic signaling mirrors, each having some means for a signaler to aim the sunlight flashes from it. The earliest aiming device was a small screen to be held in front of a part of the mirror and used to align the reflected beam of sunlight. In 1942 Mr. L. L. Young of the National Bureau of Standards and Mr. W. M. Potter[1] of the General Electric Company developed a method of aiming which required that the mirror reflect on both sides immediately around the sighting hole. Several months after this development, Mr. C. H. Learned of Carmel, California, suggested to the National Inventors Council that a retroreflector of one of the types widely used in night visible traffic signs be fastened behind a clear window of a metal-on-glass mirror. Because part of the light returned toward the sun by the retroreflector thus placed is reflected to the rear by the glass surfaces of the window, a signaler can look past the edge of the reflector through the window and see an imperfectly formed image of the sun appearing in the direction in which the mirror is reflecting sunlight. Aiming a mirror equipped with such a retroreflector is merely a matter of turning the mirror to place this bright spot (usually colored red by the retroreflector) upon the target. Two models of this improved type of signaling mirror have been developed at the National Bureau of Standards. In the first, a reflector button is tilted at about 30° behind the mirror window; in the second, a thin washer of retroreflective material is held by a cover glass at the rear surface of the window. The first mirror must be held so that the reflector button faces roughly toward the sun before the red aiming spot can be seen, but rotation of the second mirror in its own plane does not affect its performance. Sample mirrors will be available for inspection.

[1] W. M. Potter, "Solar Searchlight," Gen. Elec. Rev. **47**, 7 (May, 1944).

Session on Color

38. Invited paper, entitled "Some Basic Ideas in Color Measurement," by DAVID L. MACADAM, *Eastman Kodak Company.*

39. Response Curves for Types of Vision According to the Müller Theory. DEANE B. JUDD, *National Bureau of Standards.*

There have been derived, chiefly from the work of Pitt,[1] three functions of wave-length which permit easy definition of the samples of radiant energy found to be identical (metameric) not only by the I.C.I. standard observer but also by the two most common types of red-green-blind observers, protanopes and deuteranopes.[2] These functions were chosen from the triple infinity of possible choices

because of their simplicity, and it was shown that they conform to the theoretical views adopted by König[3] in 1897. In accord with those views the properties of tritanopic vision also can be simply derived from them, though these properties are less precisely known than those of normal, protanopic and deuteranopic vision. It has been found possible also to express these properties of normal and dichromatic vision in a form consistent with the theory of vision developed by G. E. Müller.[4] According to this theory light stimuli affect the visual mechanism initially by eliciting three different primary sensitizing processes (*P*-processes) in the cones. The strengths of these primary processes are determined from the wave-length of the incident radiant energy according to functions similar to those defining the three components of the Young-Helmholtz theory whose connection to the I.C.I. standard observer is already known approximately.[5] According to the Müller theory these primary sensitizing processes contribute immediately to excitation of a black-white "substance" of the optic-nerve fibers in the sense of producing white. They also act upon certain chromatic sensory substances in the cones of the normal eye to elicit a yellowish-red process whose negative is bluish-green and a greenish-yellow process whose negative is reddish-blue. These chromatic sensory processes serve to excite red, green, yellow, and blue excitations of the optic nerve, and contribute also to the black and white excitations. The Müller theory corresponds therefore to three stages of excitation, the first of which is the same as the Young-Helmholtz formulation. The coordinate systems for the other two stages are overdetermined by conditions described by Müller, but the several conditions agree well. Response curves fulfilling these conditions have been derived and yield a prediction of tritanopic luminosity function which could form a test of the validity of the assumptions made by Müller.

[1] F. G. H. Pitt, "Characteristics of Dichromatic Vision," Medical Research Special Report Series, No. 200 (London, 1935).
[2] D. B. Judd, J. Research Nat. Bur. Stand. **33**, 407 (1944) RP1618.
[3] A. König, Ges. Abh. (Barth, Leipzig, 1903), p. 396.
[4] G. E. Müller, *Darstellung und Erklärung der verschiedenen Typen der Farbenblindheit* (Vandenhoeck and Ruprecht, Göttingen, 1924).
[5] D. B. Judd, Illum. Eng. **36**, 336 (March, 1941).

40. The Measurement of Specular Reflectance with a General Electric Recording Spectrophotometer. DONALD M. PACKER AND FRIEND H. KIERSTEAD, JR.,* *Optical Design Laboratory, U. S. Naval Gun Factory.*

A method has been developed whereby absolute values of specular reflectance may be obtained with a General Electric recording spectrophotometer. An extra cup is constructed to fit the portholes of the specular integrating sphere and is filled with the same material (magnesium oxide or carbonate) as that used in the block receiving the comparison beam. In making a measurement, the machine is adjusted as usual with the auxiliary cup placed at the rear sphere port to receive the measuring beam. The cup is then transferred to the front port, replacing the cup usually closing this opening, where it will receive all of the measuring beam specularly reflected from the sample which is positioned at the rear port. The reflectance curve is then run off in the usual manner. Since the measuring beam is reflected from the same cup (before being diffused into the sphere) during both adjustment and measurement, the method differs from the measurement of transmission only in that the measuring beam is attenuated by reflection from the sample, instead of by transmission through it. The results obtained by this procedure are therefore absolute in the same sense as are the results of a transmission measurement. In conjunction with the development of the foregoing procedure, a method was devised for measuring specular reflectances of single glass surfaces. A right-angle prism is used as in a Porro-prism inverting system with half the hypotenuse serving as the reflecting surface. The other two faces are painted with asphalt or non-scattering black lacquer. The light which enters the prism through the reflecting surface traverses it as in the Porro arrangement and is absorbed by the multiple reflections from the painted surfaces. This provides a convenient means for the measurement of efficiency of reflection-reducing films, for one-half of the prism hypotenuse may be coated while the other half is left uncoated to provide a reference surface. Calibrated black glass is employed as the reference standard of reflectance in the measurement of low-reflection films.

* Now in the Armed Forces.

41. A Device to Facilitate the Reading of Spectrophotometric Curves. GENEVIEVE REIMANN, *National Bureau of Standards* AND EARLE J. CARMINE, *Davis Instrument Manufacturing Company, Baltimore, Maryland.*

The reading of spectrophotometric curves, such as those obtained on a GE recording spectrophotometer, is tedious, time-consuming, and often the cause of eye-strain. A mechanical and optical device has been developed which overcomes these drawbacks to a considerable extent. By this means, magnified images of the spectrophotometric curve, the reflectance scale, and the corrected wave-length scale are brought into approximate juxtaposition so that a point on the curve may be easily and quickly read. The essential features consist of: (1) a horizontal mechanism supporting a rectangular, adjustable lens mounted above an etched hair-line, permitting setting on the wave-length scale to .05 mμ, (2) a vertical mechanism with fine and coarse adjustment by means of which any curve on the record sheet may be brought under the lens for reading, (3) a movable reflectance scale, and (4) a removable wave-length scale by means of which a wave-length correction may be readily applied. The whole apparatus is portable and mounted on an adjustable stand, which can be tilted and locked at any angle suitable to the operator. All movements can be made with the left hand, leaving the right free for recording data. The device may be used with or without the wave-length corrections and is applicable to either the weighted or selected ordinate method of reading. The equipment was developed primarily for the reading of spectral curves of textile samples. In general, these curves are not as steep as, for example, those of signal glasses and dyed plastic samples. To make the present model more convenient for reading all types of curves, the vertical movement should be made to operate with the

same ease and speed as the horizontal movement. Other contemplated improvements in design, brought out by several months' use, include a more rapid means of lining up the paper and equipping the device with a mechanical counter. The apparatus in its present form has served to increase notably the speed of reading, particularly when there are several curves to a sheet; and use of the device is considerably less tiring than any other method which has been tried.

42. Method for the Spectrophotometry of Reflection-Reducing Films on Prisms. HARRY J. KEEGAN, *National Bureau of Standards.*

The first surface reflectance of the specular component from a magnesium fluoride film deposited on the hypotenuse face of a military binocular prism may be accurately measured in conformance to Army and Navy specifications[1] on the General Electric recording spectrophotometer by the use of special techniques similar to those developed for MgF_2 films on flat glass plates.[2] Three types of measurement have been considered (1) the direct determination of the index of refraction of the film, (2) the measurement of the spectral transmission of the coated and the uncoated optical parts, and (3) the measurement of the spectral reflectance of the coated surface. It is understood that the first type of measurement is unfeasible because the film cannot be separated from the glass. The second method assumes that both the film and the glass are non-absorbing and that the reflectance is equal to one minus the transmission. The third method and the one discussed herein is considered to be the more direct determination especially in the present case of the Porro prism. Because of the relatively small aperture of this type of prism, the incident light beam is diaphragmed with black paper of about 4 percent reflectance to a rectangular aperture of approximately 1/2 inch in height and 1/4 inch in width. A spectacle lens of about 10 diopters is placed in the transmission compartment of the instrument so that the image of the lamp filament is centered on the aperture of the diaphragm covering the prism face. A little of the filament image is allowed to extend onto the black paper diaphragm to bring the "zero" spectral reflectance curve of the aperture cavity out of the region of uncertainty on the photometric cam for low reflecting materials.[2] The main beam, incident at 6° on the face of the vertically placed prism, is occulted by the diaphragm and all of the successively reflected and multiple reflected components of the beam are directed away from the sphere opening and only the specular component of the first surface reflection is allowed to reenter the integrating sphere. It should be noted that at no time during the procedure is the photometric scale of the instrument changed from its calibrated state. However, to eliminate the effect made on the measurements by the black paper diaphragm and to convert the reflectances of the coated prisms into terms of reflectance derived from the Fresnel formula, a working standard of polished optical black glass (or blank, uncoated prism) of known refractive index must be used.

[1] O. S. 1357. Specification for reflection-reducing films produced by the evaporation process, revision A of November 23, 1942. Navy Department, Bureau of Ordnance. 18G7 (INT), Glass-surfaces, optical treatment of, February 1, 1943. Navy Department, Bureau of Ships ad interim specification. 51-70-4A, Films, reflection-reducing, for glass optical elements. War Department, Chief of Ordnance, Army Service Forces, Washington 25, D. C.

[2] H. J. Keegan, "On the measurement of the spectral apparent reflectance of low reflecting materials," J. Opt. Soc. Am. **34**, 770 (1944).

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Minutes of the Twenty-Sixth Meeting of the Board of Directors of the Optical Society of America, Incorporated

HOTEL PENNSYLVANIA, NEW YORK, NEW YORK, OCTOBER 17, 1945

IN addition to the transaction of routine business, the following items of general interest to members of the Society were considered.

Announcements by Secretary

Results of letter ballots:

1. Approved nomination of Deane B. Judd as O.S.A. Representative on the Division of Physical Sciences of the National Research Committee for a three-year term beginning July 1, 1945.
2. Approved resolution to hold annual meeting in New York City on October 18, 19, and 20, 1945.
3. Approved appointment of Program Committee for annual meeting in October, 1945, consisting of Norman Wright, Chairman, G. R. Harrison, H. H. Nielsen, Herbert R. G. Grosch, and John E. Tyler.
4. Approved resolutions to declare the present Secretary and Treasurer eligible for re-election in October, 1945.
5. Approved resolution to award Frederic Ives Medal for 1945 to Dr. W. W. Coblentz.

Announcement by President

Appointment of Tellers for 1945 election:

S. Q. Duntley, Chairman	D. C. Stockbarger
H. M. O'Bryan	W. B. Nottingham, Alternate

Report of Tellers

The report indicated the election of the following officers:

For a term of two years—

President	G. R. Harrison
Vice President	Rudolf Kingslake

For a term of four years—

Secretary	Arthur C. Hardy
Treasurer	W. W. Graeper

Members-at-large of the Board of Directors:

Frank Benford
F. M. Bishop
Wallace Brode

Appointment of Associate Editors

The following Associate Editors of the Journal were appointed for a term of six years commencing January 1, 1946:

W. R. Brode	W. B. Rayton
K. S. Gibson	R. A. Sawyer
G. H. Gliddon	E. D. Tillyer
Selig Hecht	Norman Wright

Membership

The Secretary reported informally a net gain in membership of forty-eight between January 1 and October 1, 1945. On recommendation of the Committee on Transfer, fifteen associate members were approved for transfer to regular membership. The names of those transferred will appear in the annual report of the Secretary for 1945.

ARTHUR C. HARDY, *Secretary*

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